

# **Laser Sounding from Space**

## **Report of the ESA Technology Working Group on Space Laser Sounding and Ranging**

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# Executive Summary

Active laser remote sensing from space is recognised to be one of the most promising new means of obtaining essential atmospheric and geophysical parameters on a global scale. Laser remote sensing of the atmosphere is referred to as **LIDAR**, the acronym of **L**ight **D**etection **A**nd **R**anging, similar to **RADAR**. In lidar, a laser light pulse is sent into the atmosphere and used as a spectroscopic probe of its physical state and chemical composition. The emitted laser beam interacts with the atmospheric constituents, causing alterations in the intensity, polarisation and wavelength of the backscattered light. The distance to the scattering medium can be deduced with high accuracy from the time delay of the return signal.

Spaceborne lidars have the potential to make significant contributions to meteorology and climatology because of their ability to provide global data on a variety of atmospheric observables such as height, horizontal extent and density distribution of scattering layers (e.g. clouds and aerosols), vertical humidity, temperature and pressure profiles, as well as wind fields in the troposphere and lower stratosphere. In addition, spaceborne lidar systems may be of great use in geodesy, as lidar returns from the Earth's surface may yield valuable altimetry and surface topography data.

Spaceborne lidars will complement or extend the capabilities of current space-based sensors for Earth observation in many cases. The excellent vertical resolution of lidar measurements allows accurate height assignments to be made for atmospheric features. This would significantly improve the data obtained from other sensors such as sounders and imagers, which generally have poor height resolution. In addition, lidars, being active instruments, can operate both in the dark side of a satellite's orbit as well as in the sunlit portion, thereby increasing the useful coverage of observation. Conversely, however, lidars will not provide data below optically thick layers (e.g. clouds).

European lidar technology has made considerable progress in the last decade and in many aspects is at least as advanced as any work worldwide. Both ground-based and airborne equipment have been deployed in the field by several European centres for extended periods of measurements, and have shown good performance and reliability. There is thus a strong scientific, technological and industrial base within Europe from which space lidar systems can be developed.

At the same time, there has also been a major evolution in the means by which missions involving laser remote-sensing systems can be realised. The advent of the Polar and Co-orbiting Platforms of the International Space Station provides a unique opportunity for carrying out such missions. In the light of these developments, ESA has set up a working group, the *Technology Working Group on Space Laser Sounding & Ranging*, composed of scientists, users and laser instrumentation specialists, with the task of advising the Agency on requirements and development priorities in the area of laser remote sensing. The Group's charter also included the elaboration of an implementation plan for spaceborne laser monitoring systems, together with the identification and examination of flight opportunities. The Working Group focused its attention on four lidar systems considered as good candidates for space deployment:

- (a) a simple backscatter lidar - for measurements of cloud top height, cloud extent and optical properties, planetary boundary layer and tropopause height, aerosol distribution - with wide applications to meteorology and climatology
- (b) a differential absorption lidar (DIAL), providing high-vertical-resolution-measurements of humidity, temperature and pressure

- (c) a wind-profiling lidar with the unique capability of improved weather forecasting and global dynamics
- (d) a ranging and altimeter lidar for very accurate measurement of surface features, including ground, sea and ice cap height for solid-Earth studies.

Each of these four lidar systems could potentially become available for space operation within the next decade and would be suitable for a variety of platforms operating from both polar orbit and equatorial orbit. To achieve space deployment within this period, immediate investment in laser and lidar technology is required; this includes work generic to all space lidars as well as mission-specific developments.

The Working Group endorses actions already undertaken by ESA for the development of high-brightness, narrow-band, tunable solid-state laser systems and strongly recommends two different types of actions that have to be undertaken immediately:

- technology developments in identified critical areas (lifetime, reliability) for two instruments :
  - \* backscatter lidar
  - \* wind Doppler lidar leading to the realisation of breadboard models;
- system or subsystem studies (mirror technology, pointing accuracy, scanning and lag angle problems ) including potential scientific studies for a better assessment of future technology developments.



# Chapter 1

## Introduction

In the early 1960's the discovery and rapid development of solid-state laser sources (e.g. ruby) led almost immediately to the first atmospheric application. A simple **LIDAR** (**L**ight **D**etection **A**nd **R**anging) was used to provide range-resolved information on the aerosol particles in the atmosphere based upon elastic scattering of the laser emitted light. At the same time, application of lasers in solid-Earth physics and use of artificial satellites offered the possibility of positioning points on the Earth's surface in a global geocentric frame of reference. The atmospheric measurements were further extended to trace species using the Raman scattering technique. In the early 1970's the advent of powerful wavelength-tunable laser sources opened up a new field for atmospheric lidar. High-resolution spectroscopic studies were made possible based on non-elastic interaction processes (resonance, resonance-fluorescence) or absorption properties. These led to the determination of trace species concentration and atmospheric state parameters at various altitude levels in the atmosphere. More recently, measurements of the Doppler shift of the backscattered light using frequency stable sources and coherent detection have allowed the measurement of the wind components throughout the depth of the atmosphere.

Though oriented towards technology development in the early days, applications of lidar to atmospheric research (meteorology, climatology, boundary-layer physics, pollution, visibility, radiative budget, middle-atmosphere dynamics and chemistry) and solid-Earth research (crustal movement, gravity field, Earth kinematics and mapping) now constitute the major activities of a worldwide community. The operational character of most of the systems (ground-based, mobile or airborne) demonstrates a maturing field of technology with a large variety of potential scientific applications.

Based on our present understanding of the Earth's environmental system, many kinds of observations are needed to allow global modelling and simulation of the long-term effects of man's activities. Future space projects for remote sensing of the Earth's atmosphere will concentrate on the operational observation of atmospheric variables fundamental to weather forecasting and climatology. Spaceborne lidars offer unique possibilities in these fields as they can advantageously complement passive sensors due to their ability to perform depth-resolved measurements with excellent vertical resolution. In solid-Earth research, the phenomena to be observed by space laser techniques include recent crustal movements, the Earth's gravity field and point positioning for mapping. Such observations will contribute to the solving of key problems in Earth kinematics.

The concept of putting lasers into space was studied as early as 1974 by both ESA and NASA. These projects did not progress very far primarily because of the inadequate performance and insufficient reliability available at that time, but also because too ambitious measurement programmes were proposed. In recent years, however, space-based lasers have received increasing attention for several reasons:

- Laser technology has now matured to a degree where the feasibility of its future use in space can be considered with growing confidence from both an operational and a reliability point of view. Solid-state lasers in particular have reached overall performance and reliability levels that were inconceivable 10 years ago. Thanks to continued progress in the development of new laser materials and thanks to the advances in diode-laser array technology for laser pumping, still further improvements in performance and reliability are ex-

pected. For the 10  $\mu\text{m}$  wavelength, development of catalysts for CO<sub>2</sub> gas lasers provides greatly increased laser lifetime, and the frequency stability of CO<sub>2</sub> lasers has been improved through better understanding of discharge mechanisms and resonator design.

- As pointed out above, the already demonstrated feasibility of ground-based and airborne lidar measurements constitutes a strong experimental basis, from which extrapolation to spaceborne systems looks quite reasonable.
- Large space platforms – such as the Columbus Polar Platform or Co-orbiting Platform – with increased weight, volume and power capacities will be available in the mid 1990's which will be particularly well suited for large active instruments.

ESA and National Space Agencies have been sponsoring various research and development projects in space laser technology in recent years, the results of which are already becoming apparent in terms of demonstration hardware and proof-of-concept instrumentation. Against this background, in March 1984 ESA organized an international meeting called **SPLAT** (SPace Laser Application and Technology) where the current situation in spaceborne laser technology was reviewed and recommendations formulated for further action. One of these was to establish a *Space Lidar Working Group* composed of laser and lidar system scientists, meteorologists, and solid-Earth physicists, charged with:

- compiling the requirements of science and user community, reviewing present/planned national activities, assessing existing feasibility studies and reviewing state-of-the-art technology;
- studying representative mission implementations, providing elements for mission, system and instrument studies and exploring possibilities for harmonisation with national efforts;
- outlining an implementation plan for spaceborne laser systems, examining flight opportunities, and making proposals for a technology-demonstration programme.

Such a Working Group was indeed constituted in September 1985, and met several times thereafter. The present document summarises the conclusions reached by this Group, which focussed on:

- laser sounding of the atmosphere (lidar), for application to meteorology, climatology and atmospheric chemistry;
- satellite-to-ground ranging (e.g. laser altimetry, topographic mapping, etc.) for geodynamic studies.

# Chapter 2

## Scientific Rationale

At the present stage of its development, a lidar system is a relatively large, complex and rather costly instrument, and the construction of a spaceborne system should thus be based on a strong scientific rationale to meet some of the specific requirements of present-day atmospheric or solid-Earth physics. Therefore, before considering the numerous possibilities of spaceborne lidar systems in Chapter 3, the scientific needs for meteorology, climatology, environmental studies and solid Earth will be briefly reviewed. They have been studied extensively by various committees and working groups during the last two or three years, and the main objective here is merely to present an overview of the future requirements based on the most recent understanding of atmospheric and geophysical processes. Furthermore, such a study needs to be rather prospective as the time frame for the development of an operational spaceborne lidar is consistent with a launch in five to ten years from now, depending on the complexity of the system and on platform availability.

Four major fields of application can be identified in the domain of laser remote sensing from space:

- Weather prediction, including local short-range prediction.
- Climate studies with the possibility of predicting monthly and seasonal anomalies and of determining the response of climate to changes in surface and atmospheric properties.
- Environmental studies with a strong emphasis on global atmospheric chemical cycles, particularly those that appear to influence global and regional climate.
- Solid-Earth research.

In recent years, the use of space observations for meteorological studies and weather prediction has increased significantly. In the early days, the first satellites gave only a synoptic scale description of the perturbed systems through simple imagery. Used in a qualitative way, they already allowed a reduction in the grid of the traditional observation network and thus a better understanding of various processes, previously undetected. Almost ten years passed before quantitative determinations of the atmospheric state-parameters could be made using spaceborne passive sensors. Some of these now compare rather well with in situ observations, and the usefulness of space data to increase the quality of short-term weather prediction has been objectively demonstrated. For example, various simulations performed during the FGGE project (First GARP - Global Atmospheric Research Program - Global Experiment) show that, using temperature and winds as determined by satellite observations, the prediction limit was increased from 5.1 to 6.5 days in the Northern Hemisphere and from 3.2 to 5 days in the Southern Hemisphere (WMO/ECMWF Report on Data Assimilation Systems and Observing System Experiments with Particular Emphasis on FGGE, 1984).

However, the lack of high spatial and temporal resolution and the current accuracy of these passive-sensor measurements do not allow a better understanding of the elementary processes that govern the evolution of the medium- or large-scale meteorological systems: deep convection, convective-cell organisation, squall-line generation, cyclogenesis and interactions with the mean circulation. Similarly, the extension of reliable forecasts beyond 5 to 6 days requires a better definition of the initial state of the various meteorological fields and an accurate parametrisation of

## 2.1 Meteorology

the physical processes responsible for the energy transfer on scales smaller than the grid of the simulation models. This is a research field involving the interactions between radiation, dynamics and changes between different water phases which is also related in many respects, as will be seen later on, to climate studies.

Satellite observations will in the future constitute the main element of the meteorological observation system. The evolution of this system until 1995, based on the complementarity of geostationary and polar-orbiting satellites, is quite predictable. Present day techniques such as multispectral imagery (medium-scale resolution on both types of satellites), surface-temperature measurements and wind-field determinations will continue to be used. Some evolution of existing systems is also to be expected in the form of an infrared temperature sounder, and a microwave temperature and humidity sounder (AMSU-B) with an all-weather measurement capacity. Experimental satellites (ERS-1, TOPEX/POSEIDON, etc.) will also allow new instrumentation, especially that for the measurement of physical quantities (latent or sensible heat fluxes) characteristic of the interactions between the atmosphere and the ocean, to be tested. Furthermore, improvements in the inversion algorithms due to the complementarity of such measurements are to be ex-

Table 2.1. Global observational data requirements for global meteorological and climate observing systems by the year 2000

		Horizontal	Vertical resolution	Observational error (rms)	Frequency of observation
i.	Upper-air temperature (T)	250 km	10 layers in troposphere 5 layers in stratosphere	0.5–1°C trop. 1–2°C strat.	2–4 per day
		(100 km)	(500 m to 2 km) (1 km to 15 km) (3 km to 40 km)		(4 per day)
ii.	Upper-air wind vector (V)	250 km	10 layers in troposphere 5 layers in stratosphere	1–2 m/s trop. 2–3 m/s strat.	2–4 per day
		(100 km)	(500 m to 2 km) (1 km to 15 km) (3 km to 30 km)		(4 per day)
iii.	Upper-air relative humidity (RH)	250 km	4 layers	30% but better near surface	2–4 per day
		(100 km)	(5 layers)	(10%)	(4 per day)
iv.	Sea-surface temperature ( $T_s$ )	250 km		0.5°C	Instantaneous measurements averaged over 3 days
v.	Surface pressure, temperature and wind vector	250 km		0.2% pressure 0.5°C temperature 1–2 m/s	4 per day
		(100 km)		(0.1% press.)	(8 per day, particularly where spatial requirement not met)

pected, allowing a more accurate determination of the individual state variables. Nevertheless, important gaps will still exist which will have to be filled in the coming decade (1990-2000) if the global observational data requirements outlined in Table 2.1 are to be fulfilled.

Three main aspects can be considered here:

(i) **The water distribution**, which includes the distribution of water vapour in the atmosphere, the capacity of the surface to release water, the distribution and water content of clouds (liquid and solid phase), and the precipitation distribution. Visible and infrared radiometry is already not sufficient and the AMSU microwave temperature and humidity sounder is not going to provide all the answers. Active systems such as the radar for precipitation measurements and the lidar, and other passive microwave systems will have to be developed.

(ii) **The motion field**: The only measurements presently obtainable are deduced from cloud motions at a given level as seen from a geostationary orbit. The scatterometer developed for ERS-1 will provide data on sea-surface winds. However, a new concept such as an active Doppler lidar is the only one that could measure the three-dimensional wind field throughout the depth of the atmosphere (troposphere and lower stratosphere) with the appropriate spatial and altitude resolution.

(iii) **The pressure/mass field**: Derivation of accurate values for the geopotential field will require improvements over the data obtained so far from infrared passive sounders. Progress in this area will probably be achieved from a tight association of passive sensors such as AMSU and high-resolution active sounders. Furthermore, the determination of the surface pressure to provide a reference level for passive observations requires the development of an active microwave or optical sounder (lidar).

Study of the Earth's climate does not rely on individual meteorological systems, but on an ensemble average of the internal states of the different subsystems such as the atmosphere, ocean and cryosphere. Their variability could in principle be separated into a deterministic component and a random one associated with weather fluctuations. The complexity of such a system is then dependent on several factors:

(i) the atmosphere is characterised by different spatial scales, ranging from local turbulence to planetary waves;

(ii) the physical characteristics of the climatic subsystems, although quite different, are strongly coupled via energy, momentum and matter transfers on various temporal and spatial scales;

(iii) a large number of unstable rapidly growing perturbations can be generated at any time, destroying the stable mean state of the atmosphere.

It is well recognised today that, even if the atmosphere is the climatic system component with the shortest time response to external perturbations, it is not possible to reduce the whole system to this single component even for the study of processes with time scales of the order of a month. Taking into account the strong coupling with the ocean, the minimum internal subsystem will include these two components, whereas the cryosphere, the biosphere and the solid Earth could still be considered as external driving factors for time scales shorter than a year. It has to be pointed out, however, that if the general circulation models of the atmos-

## 2.2 Climatology

phere are already at an advanced stage of development, the active coupling with the ocean and the biosphere are still not taken into account due to the lack of understanding of the oceanic general circulation. This gap should be filled within the next decade by such large international programmes as TOGA (Tropical Ocean and Global Atmosphere) and WOCE (World Ocean Circulation Experiment), which are based on a coherent set of both in-situ and satellite observations and on modelling of the processes on the various spatial scales involved (Scientific Plan for the World Climate Research Program, WCRP Publication, WMO/TD No 6, 1984). The present state of equilibrium of the climatic system can be described from the various budgets of the main variables, i.e. energy, momentum and matter, especially water. Solar radiation is the main external driver and the global radiative equilibrium requires the transport of heat from the equator towards the poles. The oceans play the role of a moderating element due to their thermal inertia and their ability to store energy. The atmosphere can then be considered as the thermal engine that redistributes this energy between the tropics and the high-latitude regions. The importance of the hydrological cycle in these various transfer processes is related to the presence of water in its three physical states: vapour, liquid and solid. The main sources of water vapour are the tropical oceans, whereas condensation and precipitation occur, after transport by the mean atmospheric circulation, in the sink areas (from the inter-tropical convergence zone to high- and medium-latitude regions associated with the polar front). The cycle is then closed through its terrestrial component (run-off, evapotranspiration, etc.).

Beside the roles of the oceans (see above) and of the biosphere (Section 2.3), two main fields of research can be identified:

- **The radiative budget** of the Earth and the vertical distribution of radiative properties should be established, including measurements of incident solar flux, scattered flux from the surface and the atmosphere, and infrared thermal radiation. Only space observations can provide a global budget at the top of the atmosphere and help in determining the temporal and spatial variations related to the equator-to-pole gradient and to the outgoing radiative flux, which is directly dependent on many atmospheric (temperature, humidity, cloud cover) or surface parameters (emissivity, albedo). The relationships between radiation and clouds or aerosol particles need to be studied with a high degree of priority in the light of the newly established ISCCP (International Satellite Cloud Climatology Project) and IACP (International Aerosol Climatology Project) projects, which are part of the World Climate Research Programme (Scientific Plan for the World Climate Research Programme, WCRP Publication, WMO/TD No. 6, 1984). Here lidar systems might play a very important role, due to their inherent high sensitivity to scattering layers in the atmosphere.
- **The hydrological cycle** has to be studied on a global scale, including quantification of evaporation, evapotranspiration, precipitation and run-off processes, and determination of the main factors that control the water equilibrium in its different phases (thermal equilibrium, general circulation, etc.). At the present time most of these parameters are not determined with the required accuracy and resolution, even to establish climatologically significant means. Remote-sensing systems including active sounders (precipitation, humidity, evaporation rates) and multispectral imagers (surface temperature, albedo vegetation index) are to be developed for such applications.

In recent years concern over mankind's vulnerability to changes in the Earth's environment has been increased by the realisation that man's activities might also be influencing his environment. The volumes of various compounds (oxygen, carbon, nitrogen, sulphur, chlorine, phosphor) are modified by the release of source constituents due to agricultural and industrial practices. Large uncertainties in the intensities of the sources and sinks of these constituents, together with their natural variability in the coupled atmosphere—biosphere—ocean system, do not allow an accurate evaluation of these global budgets at the present time.

The main impact of such modifications in atmospheric composition is on climate, as the radiative properties of the released constituents (carbon dioxide methane, chlorine or nitrogen species) or of altered species (ozone) modify the Earth's thermal equilibrium through an enhancement of the 'greenhouse effect'.

Three main questions have thus to be addressed:

- **The understanding of the elementary mechanisms** that govern the cycle of a given element, including the identification of the various natural and anthropogenic sources and sinks, and taking into account all photochemical and chemical processes that can modify their atmospheric equilibrium.
- **The impact of human activities** has then to be determined, using various scenarios for the evolution of the constituents as a basis. Due to the global nature of the problem, space observations will play an important role in helping to identify the various productive vegetation areas (both land and oceanic surfaces) and their evolution.
- **The estimation of emission fluxes** based on a parameterisation, which should include the various surface parameters (vegetation index, water content in the soil, albedo) and atmospheric variables.

Such observations will be undertaken in conjunction with in-situ validation in the framework of the ISLSCP (International Satellite Land Surface Climatology Project, WMO/TD Publication No. 46, 1985) and, in the near future, the International Geosphere-Biosphere Program (IGBP).

## 2.3 Environmental Studies

With the availability of artificial satellites to assist modern geodesy, precision in the determination of the positions of reference points and in the measurement of mutual distances between two points thousands of kilometres apart, has increased by orders of magnitude. With today's laser ranging techniques, it is possible to perform such a determination with an accuracy of better than one centimetre. Measurement systems capable of carrying out measurements with millimetre accuracy are presently being designed.

Possible missions for a European Solid-Earth Programme have been studied and recommended in the Solid-Earth Working Group, and its analysis and recommendations are given in a report entitled "Recommendations for a European Long-Term Space Programme in Solid-Earth Science and Applications" (ESA/SEWG (85) 1). A summary of its conclusions also appears in "Looking Down - Looking Forward" (ESA SP-1073, January 1985). The objectives and recommendations of the above reports were confirmed in March 1986 at an ESA Special Workshop on "Solid-Earth Science and Application Mission for Europe (SESAME)", the Proceedings of which are available as ESA publication SP-1080.

The scientific objectives include :

## 2.4 Solid-Earth Research

- the dynamics of the lithosphere
- physical processes in the mantle
- core-mantle interaction.

The **applications** include:

- mapping and charting control
- precise positioning for offshore activities
- mineral-resource exploration (seismographic sounding)
- deformation monitoring of hazardous structures
- precise orbit determination for applications satellites
- earthquake prediction research
- real-time monitoring of sea surface topography (ship routing)
- geophysical data collection.

The **achievement** of these objectives requires:

- precise positioning capability
- detailed knowledge of global gravity and magnetic fields
- accurate determinations of Earth rotation parameters (polar motion and length of day)
- precise altimetry.

The main parameters, together with the observational accuracies and sampling rates required, are given in Table 2.2. The accuracy requirements call for the most sophisticated measurement techniques, particularly for measurement of motions of the lithosphere. The measurement of time-dependent crustal deformation in a number of the major tectonically active regions is a typical candidate, since it requires systems that not only provide the necessary precision in the determination of control points, but also provide a sufficiently large geographical coverage combined with repetitivity in the monitoring operations. Different ground grid sizes in such regions can be considered for different operational requirements:

- regional (500 km)
- sub-regional (50-500 km)
- local (10-50 km).

**Table 2.2. Solid-Earth objectives and measurement requirements**

Motion of the lithosphere		Accuracy	Sampling intervals
Global (5000 km)	horizontal	1–2 cm	1 year
	vertical	1 cm	1 year
Regional (500 km)	horizontal	1–2 cm	1 week
	vertical	< 1 cm	1 week
Local (50 km)	horizontal	1–2 cm	1 day
	vertical	< 1 cm	1 day
Earth rotation and polar motion		Accuracy	Sampling intervals
Conventional Celestial Reference System (CCRS)		0.0001 "	few years
Precession-Nutation (P-N)		< 0.0001 "	
Earth Rotation Parameters		0.0001 "	daily (0.5 day for diurnal nutation)
Conventional Terrestrial Reference System (CTRS)		1 cm	1 year



As far as regional and subregional grid sizes are concerned, presently employed ground-based mobile systems ranging to retro-reflector satellites, or existing and planned satellite systems with high-precision ranging equipment on board, can provide adequate performance to satisfy the research objectives. For local applications, spaceborne laser ranging techniques possibly offer a preferred solution to the problem of monitoring a number of parameters of interest for research in crustal and ice dynamics.

Table 2.3 lists typical requirements for potential close-grid geodynamic measurements. The requirements in terms of spatial resolution and sampling interval vary according to the type of application. The ranging accuracy needed varies from 1 to 2 cm to 100 cm for crustal-motion monitoring and ice-sheet positioning, respectively, with observational periods ranging from some weeks to one year. A particularly useful element for such monitoring could be a low-altitude polar-orbiting platform which, in a space-to-Earth positioning mode, surveys the regions of interest with global coverage and with a sufficiently high repetition rate. Currently planned platform resources would allow the operation of active laser systems in space.

Even for the observation of motions on a subregional scale, spaceborne laser ranging could be usefully employed in cases where the time and costs involved in using a mobile ground-based system would be large. Moreover, laser ranging from aircraft is well-suited for local-scale investigations.

**Table 2.3. Typical requirements for potential close-grid geodynamic measurement system applications**

Potential application	Accuracy (cm)	Frequency	Grid spacing (km)
Dilatancy	$\leq 1$	Quarterly	1–10
Post-glacial uplift	1–2	Yearly	10
Geodetic surveys		Yearly	10–50
Surface motions near plate boundaries		Quarterly	10
Regional strain measurements		Quarterly	10–50
Subsidence	2–5	Quarterly	1–10
Surface motions of central regions of large ice caps		Semi-annually	10–50
Unstable-slope monitoring		Weekly to yearly	0.5–10
Velocity fields of surface in major ice sheets	5–10	Monthly	10–50
Surface motions in permafrost		Weekly to monthly	1–10
Glacier flow-velocity fields		Weekly to monthly	0.5–10
Regional land boundary demarcation	10–100	Once	10
Location of stationary buoys		Quarterly	Same as depth to ocean bottom
Strain measurements of pack ice	100–1000	Weekly to monthly	1–10
Offshore boundary demarcation		Yearly	10
Navigation		Cluster of observations	50
Positioning of large sea-ice sheets, ice islands	1000	Daily to weekly	Same as depth to ocean

Another important spaceborne technique is satellite altimetry. Satellite altimeters are basically designed for measurements over water, where they provide the most precise and detailed information on the ocean geoid and ocean/sea surface, including ocean-circulation features. They are therefore also suitable for monitoring the levels of large inland lakes, which are useful indicators of climatic changes. In remote, high-altitude inland areas such as the Andes, altimeter measurements of lake surfaces would provide more accurate data than can be obtained by the usual slow and tedious methods of precise levelling, which also accumulate large errors. Although present altimeter concepts rely on microwave techniques, laser altimetry could in the future become a valid alternative or could complement microwave altimeters by making higher (horizontal) spatial resolution and high-precision (few cm) topographic measurements over ocean, ice and land under cloud-free conditions, as well as coastal-dynamics measurements. Table 2.4 summarises the observational needs of altimetric measurements for these various fields of application.

**Table 2.4. Observational needs for altimetry/ranging**

Vegetation	Application	Accuracy	Spatial resolution	Observational requirements
Vegetation	Environment, resources, land-use, planning, topography		0.1 —10 km	Daily to monthly
Surface elevation	Continental tectonics, surface processes, mapping	1 cm — 1 m	0.01—100 km	Daily to yearly
Inland and sea ice	Ice dynamics, climate		0.1 —10 km	Daily to yearly
Wave height	Air-sea interaction		1.0 —100 km	Daily

# Chapter 3

## Potential of Lidar in Space

Lidar observations have already contributed significantly to the various scientific areas that have been reviewed in the previous sections. Over the past ten years, many ground-based field lidar systems have been developed and deployed in Europe. Airborne systems have also been built and operated, particularly in France, West Germany and the United Kingdom. These systems have clearly demonstrated their measuring capabilities and reliability, indicating the maturity and strength of lidar technology in Europe. Putting a lidar in space is therefore a logical next step, and one that will yield a high scientific return at comparatively low risk and cost.

Based on the long-standing experience already available with ground-based and airborne lidars, the potential of spaceborne lidar system can readily be identified. As indicated in the introduction to this report, lidar applications now cover a wide spectrum of disciplines. In setting priorities for spaceborne lidar systems, the Working Group has taken into account the needs to:

- address as much as possible the needs in atmospheric (meteorology, climate, environment) and solid-Earth research and applications as outlined in the preceding section;
- take advantage of the unique capacities of lidar directly related to the use of a laser source (Table 3.1);
- identify the areas in which the lidar can be considered unique, thereby providing a means to fill some instrument gaps in satellite-based observations of the Earth;
- consider, with a high priority, the complementarity of lidar and passive sensors (imagery, radiometry, spectroscopic techniques) as a powerful way to increase our knowledge of atmospheric and surface parameters;
- take into account the size and complexity of potential instruments, as well as the related technology development requirements (laser source, detection package, pointing systems) and platform availability.

Various reviews of the potential of spaceborne lidar experiments have been carried out in the past few years. Table 3.2, taken from the SPLAT document, gives a summary of the potential of spaceborne lidars with respect to weather prediction, climate studies and atmospheric composition measurements. Table 3.2 also provides a rough feasibility rating in terms of both probability of success and instru-

Table 3.1. Capabilities of lidar

Lidar properties	Lidar capacity
Temporal coherence (short-pulse emission)	High vertical resolution
Spatial coherence	High horizontal resolution (Single shot probing between clouds)
Brightness	High sensitivity (due to high energy densities created at distant areas) to scattering layers in the atmosphere
Narrow linewidth emission	Day/night operation
Spectral tunability	Specific detection of atmospheric constituents

**Table 3.2. Potential of spaceborne lidars**

Experiment	Altitude range (km)	Principle	Accuracy	$\Delta Z$ (km)	$\Delta Z$ (km)	Scientific objectives*
Cloud-top height	0–15	Elastic scattering	150 m	0.15	0.15	A, B
Tropospheric clouds and aerosols	0–15	Elastic scattering	10%	0.15	0.15	B
Cirrus ice/water	5–15	Polarisation/Elastic scattering	—	0.15	0.15	B
Surface reflectance	Ground	Surface backscatter	0.1%	—	0.15	B
Surface pressure and cloud-top pressure	0–10	DIAL ( $O_2$ )	0.2%	—	20–100	A, B
Vertical pressure profile	0–10	DIAL ( $O_2$ )	0.1–0.5%	1	500	A, B
Temperature profile	0–10	DIAL ( $O_2$ )	0.7–2 K	2	500	A, B, C
	10–60	Rayleigh scattering	0.7–2 K	2	500	A, B, C
Water vapour	0–20	DIAL	10%	2	250	A, B, C
Cloud-top winds	0–15	Doppler/Elastic scattering	$\pm 2$ m/s	0.15	0.15	A, B, C
Winds (aerosols)	0–25	Doppler/Elastic scattering	$\pm 2$ m/s	1	100	A, B, C
Stratospheric aerosol backscatter profile	10–50	Elastic scattering	20%	1	300	B, C
Stratospheric aerosol composition	15–30	Differential scattering	—	5	500	B, C
Ozone vertical distribution	10–20	DIAL	2%	1	500	B, C
	20–60	DIAL	2%	1	500	B, C
Species distribution using IR DIAL	0–15	DIAL	10–20%	1	200	C
Total contents using CW/IR laser ground returns	0–30	DIAL/Long-path absorption	$\pm 2\%$	—	10–250	B, C
Trace-species measurements using two-satellite occultation	10–50	Long-path absorption	10–20%	1	200	C

\* Scientific objectives: A — Weather prediction, B — Climate studies, C — Atmospheric composition

ment complexity: the experiments are listed in order of increasing difficulty of implementation.

Compared with ground-based or even airborne sensors, the prime advantage of space lidars is the possibility to obtain rapid **global coverage**, and also to obtain data from otherwise inaccessible regions. The minimum size of the footprint of a spaceborne lidar is determined by the diffraction limit of the transmitting telescope: it can therefore be as small as a few metres, thus providing very high horizontal resolution. Larger footprints can be obtained by defocussing the laser beam, resulting in larger horizontal averaging. The position of successive footprints at ground level is obviously determined by the orbital height of the space vehicle, the optical arrangement (nadir pointing, scanning capacity), and the laser pulse repetition rate.

Lidar systems will thus provide **very high horizontal and vertical resolutions**, when used in pulsed mode. A spaceborne lidar will have the capability of **probing the troposphere between the clouds**, day and night. It is thus a very suitable instrument for **study of the lower layers of the atmosphere**. Conversely, however, useful measurements cannot be obtained below dense clouds or optically thick particulate layers, which absorb the energy of the laser beam.

The potential of several lidar systems will now be reviewed, paying particular attention to the determination of atmospheric variables related to meteorological and climate studies, which will constitute the bulk of laser remote-sensing observations from space. Various lidar instruments will be considered, and both the uniqueness of their capacities and their complementarity with other spaceborne sensors will be addressed. For the sake of completeness, other lidar systems with potential applications from space will be briefly reviewed in Section 3.4.

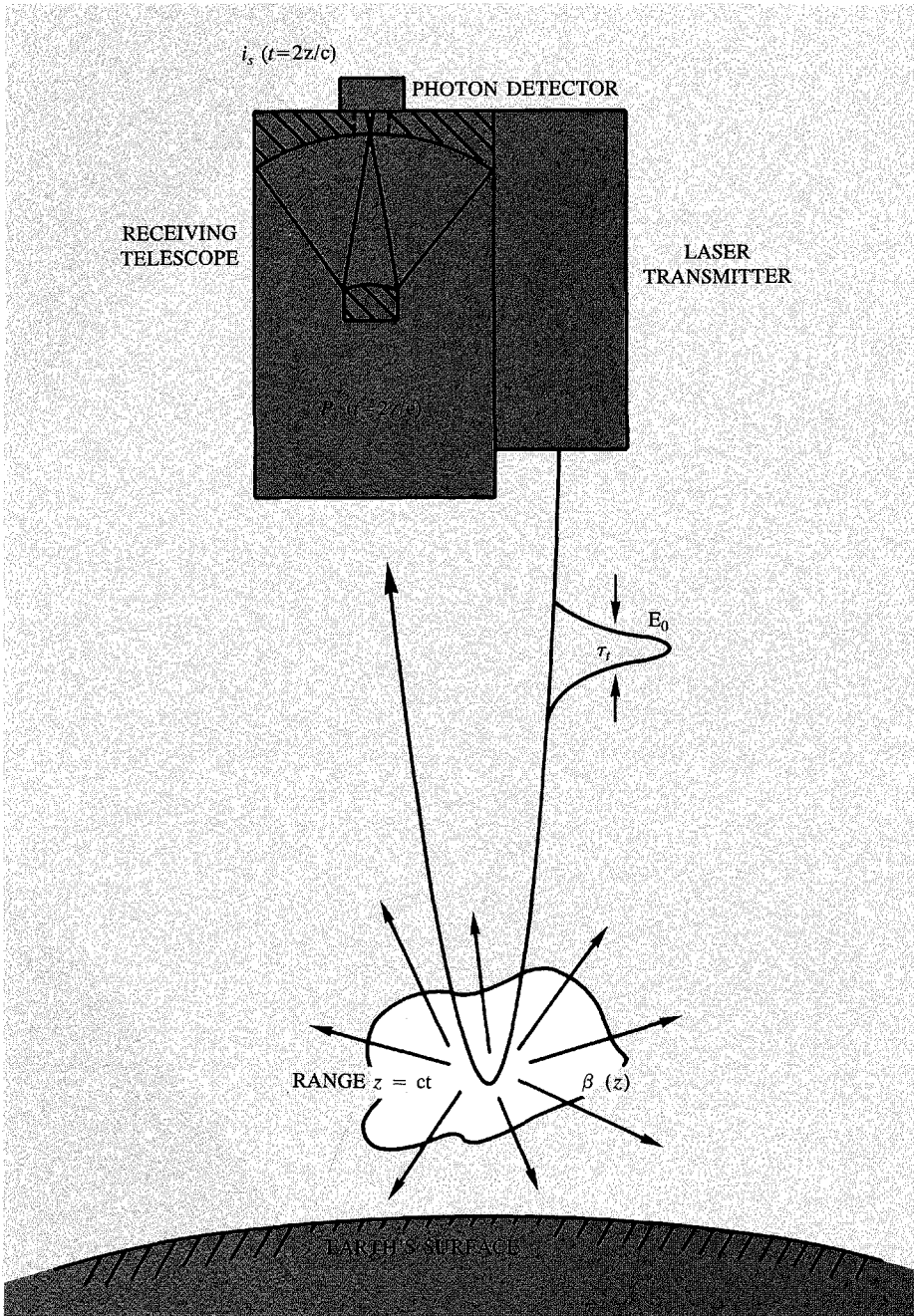


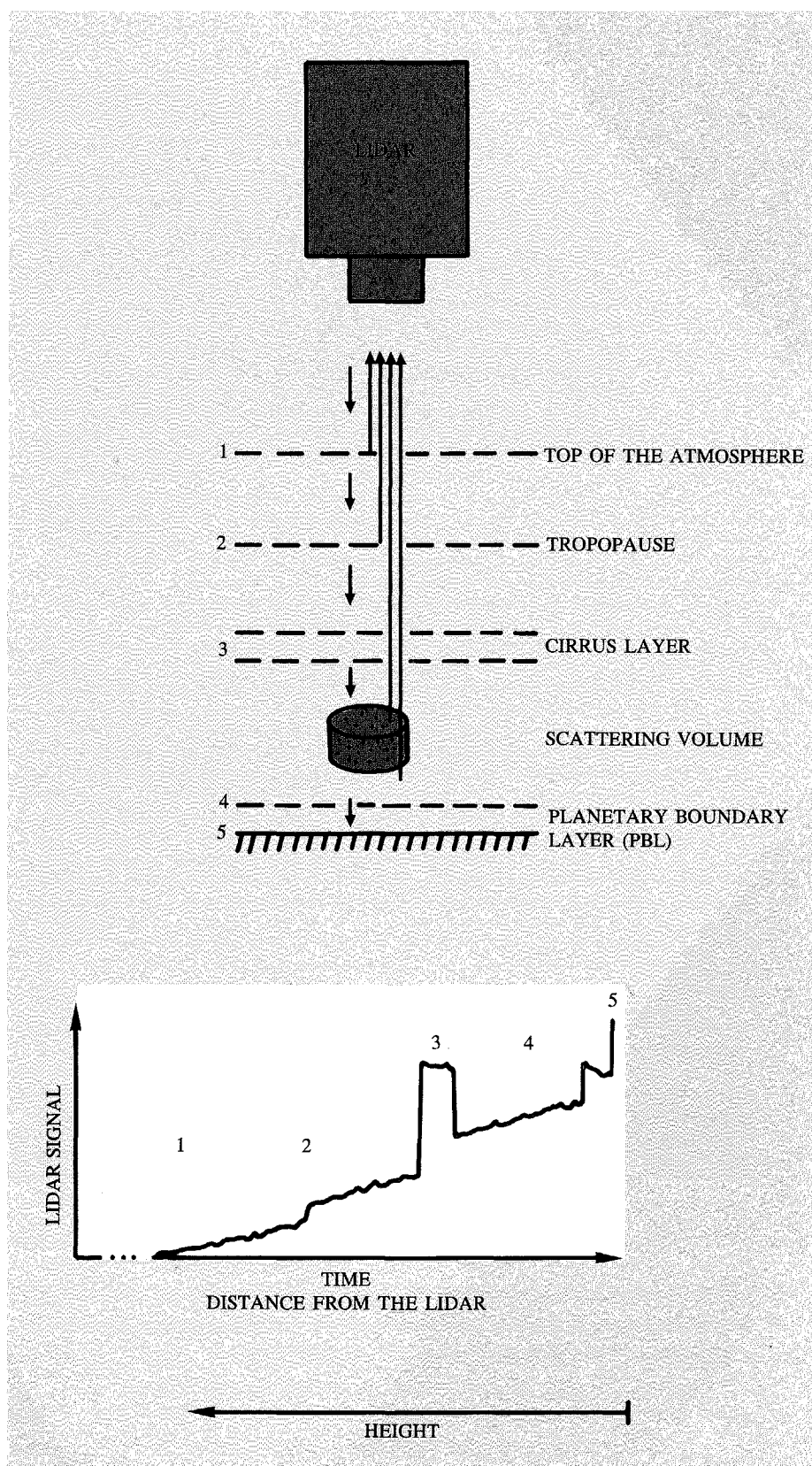
Figure 3.1. Schematic of a spaceborne lidar

A backscatter lidar provides informations on the scattering ( $\beta$ ) and extinction ( $\alpha$ ) coefficient properties of various atmospheric layers. The received power  $P(z)$  from altitude level  $z$  is simply given for single scattering by:

$$P(z) = \frac{C}{(z - z_s)^2} \beta(z) \exp(-2 \int_{z_s}^z \alpha(z) dz)$$

### 3.1 Backscatter Lidar

**Figure 3.2. Principle of backscattering lidar measurements and height profiling of atmospheric backscattered radiation via pulse timing measurements**



where  $C$  is a constant depending on the emission and reception characteristics of the lidar system, and  $z_s$  the altitude of the space platform.

In a first and simple analysis, the lidar will allow measurements with quite good spatial resolution (of the order of 100 m or better) of: cloud-top height, planetary boundary layer, bounds of temperature inversions, aerosols, subvisible clouds, etc. (Fig. 3.2). In a second step, evaluation of the backscattered lidar signals will allow the retrieval of the vertical profile of the backscatter and extinction coefficients (aerosols, cloud particles, etc.). This is a more difficult task, as such determinations using a single- or even dual-wavelength lidar system do imply an a-priori knowledge of the nature and size distributions of the particles, and have thus to rely on climatological databases and iterative retrieval algorithms.

Before elaborating on specific parameters as determined by a spaceborne backscatter lidar, one should again emphasise that such a system will be applied for two different tasks:

- Firstly, by providing altitude information for various scattering layers in the atmosphere (planetary boundary layer, cloud-top height and possibly the tropopause), it will support other passive and active sensors for the retrieval of meteorological parameters and could thus be considered part of an operational meteorological observation system for weather forecasting.
- Secondly, the intensity of the scattering and the identification of particulate layers (e.g. subvisible clouds, aerosols, etc.) will provide information for a climatological database on atmospheric properties directly related to the radiation-budget and climate studies.

Potential applications of a spaceborne backscatter lidar thus include:

#### **(a) Height of the Planetary Boundary Layer (PBL)**

The height of the PBL is often coupled with the upper level of a temperature inversion or a temperature gradient change and thus with a step in the aerosol concentration which will be detectable by lidar. Precise knowledge of this lower altitude inversion is of importance for the determination of the temperature profile from passive radiance measurements. Also the energy exchange between the ground (solid Earth, ocean) and the atmosphere related to the sensible and latent heat fluxes is an important parameter for weather, medium-range and climate models. A backscatter lidar providing the height of the PBL and its horizontal gradient will give an independent and supporting measurement to further improve the accuracy of general-circulation and regional-scale models.

#### **(b) Surface-temperature measurements and temperature and humidity profile retrievals**

The temperature of the Earth's surface, together with its albedo, determines the radiation budget at the bottom of the atmosphere and, in consequence, the energy available for sensible and latent heat fluxes and for the poleward heat transport in the oceans. In particular the sea surface temperature is one of the most important parameters because of the large water-covered areas. The estimation of surface temperatures using passive radiometers suffers from the fact that the received radiances have two contributions: one from the radiance directed upward at the surface and transmitted through the atmosphere, and one from the radiance resulting from the emission and re-absorption of the overlying atmosphere. Lidar

measurements give additional information, first on the existence itself of an aerosol layer, secondly on its height, and thirdly on the aerosol optical depth at the wavelength of the radiometer channels. Such information can be incorporated in numerical models. Lidar measurements are also of particular value if land surfaces are to be observed. As the split-window technique used over the oceans is no longer applicable, the independence of atmospheric lidar measurements from surface properties will help to improve correction for the masking atmosphere.

The vertical temperature profile is one of the most important parameters for numerical weather forecasting models. Temperature profiles are presently determined on an operational basis by passive infrared and microwave sounders such as the TOVS (Tiros Operational Vertical Sounder) instrument. The major shortcoming of such an instrument is its poor vertical resolution (2 to 3 km). In particular distinct temperature structures (e.g. inversion layers) are generally not observed.

A backscatter lidar will provide a measurement of the altitude of temperature inversions and of changes in temperature gradients by their coupling with aerosol layers. These height values can then be used as additional input data to the retrieval algorithms of passive temperature sounders. Better temperature profiles also lead to improved humidity profiles since the former serve as input parameters for the latter. Furthermore, accurate cloud-top height assignment by lidar measurements will enable better temperature profile retrievals to be made above clouds.

#### (c) Wind-field determination

Determination of the wind field is traditionally accomplished by ground-based observations (measurements with anemometers, drift of radiosondes) or by theoretical calculations (solving of dynamic equations). To get global coverage and high temporal resolution, wind velocity and direction are deduced from the movement of clouds as seen from geostationary imaging radiometers. Provided that this motion is equivalent to the wind field, the results are quite encouraging, but the estimation of cloud height might be erroneous. Here the possibility of improved cloud-height determination by lidar can help to obtain wind vectors in different atmospheric layers. The major problem will be — particularly in the case of inhomogeneous cloud fields — the correlation between the lidar measurements and the information content of satellite-sensor pixels which, in general, are of larger dimensions. Both theoretical and field studies will be required to assess this sampling problem.

#### (d) Cloud statistics

Cloud statistics are of particular importance for study of the Earth's radiation budget. It requires information on spatial properties (height, thickness, aspect ratio), cloud cover, classification and motion. The monitoring of these quantities is used to observe trends in the Earth's climate. Even today, cloud statistics are based to a very large extent on human observations from the surface and from aircraft. They are generally limited to only a small number of cloud parameters (cloud cover and cloud type); they cannot recognise different cloud layers and do not work during night. They are difficult to scale correctly because they are based on human experience.

The main difficulties in the determination of cloud parameters with standard passive remote-sensing techniques are related to the fact that: (i) the cloud is possibly not correctly identified, and (ii) the conversion from radiance measure-



ments to altitudes requires model assumptions. Furthermore, thin cirrus clouds ("subvisible cirrus") are not detectable and will lead to a wrong radiation temperature measurement (e.g. cirrus above stratiform layers).

Some of these problems can be overcome if lidar measurements are made available. As mentioned earlier, the main advantage of a lidar system is the high vertical resolution (100 m), resulting in a cloud-location accuracy that cannot be achieved by passive remote-sensing techniques. Lidar determination of cloud parameters can be regarded as a direct method which does not require complex inversion procedures. Lidar will also detect thin cirrus clouds so that the specific influence of subvisible cirrus clouds on cooling rates and atmospheric stability can be investigated and cloud statistics can be completed. Another improvement with respect to cloud classification can be achieved if the estimation of cloud types from the horizontal extent of the layer and the variance of cloud-top heights measured by subsequent laser shots proves to be successful. Furthermore, lidar experiments supply modellers with another set of data with respect to cloud parameterisation to test their theoretical approaches. Here again the spatial sampling problem arises: lidar measurements are only "pin points" compared to realistic cloud fields. If homogeneous stratus layers are observed, there will be probably a strong correlation between single laser shots and bulk properties of the cloud. However, if the cloud field is inhomogeneous, a large number of measurements and the very precise location of each will be needed to be able to characterise the clouds.

#### **(e) Aerosol measurements**

Aerosols influence the radiation budget of the atmosphere directly and indirectly via the cloud properties. They affect atmospheric dynamics and can cause misleading interpretation of other climatic parameters. Thick aerosol loading noticeably reduces the visibility within its layer. Aerosol particles reflect and absorb solar radiation and absorb and emit terrestrial radiation. Thus, the aerosols either decrease or increase both the energy received by the Earth-atmosphere system in the solar spectral range and the energy emitted in the terrestrial spectral range, leading, respectively, to global cooling or warming. The cutoff between the two cases depends not only upon aerosol absorption and backscatter, but also on ground reflectance and emission.

Within the stratosphere, aerosol extinction is monitored quasi-operationally by passive occultation methods. Within the troposphere, only nadir looking methods are possible. The advantage of lidar measurements will then be their high vertical resolution and their independence from surface properties. For aerosol determination, this may lead to the following improvements :

First, lidar signals give information on the height of aerosol layers. This information improves the passive determination of the aerosol optical depth to a certain extent. Secondly, lidar signals may provide a method of deriving aerosol extinction coefficients. These can be used independently or in addition to passive measurements. Passive methods work only during day-light conditions, while active methods result in more precise values during night. Passive and active methods use different parts of the phase function. Thus, their combination may improve both results. Thirdly, the use of double-frequency lidar measurements, which can be performed rather easily, will improve the information on aerosol size distribution and on the contribution of Rayleigh scattering and absorption by gases and particles.

**Table 3.3. Potential areas of application for backscatter lidar**

Scientific Goal or Quantity determined	Wave-length desired	Additional Sensors	Areas of Application	Studies needed
Cloud Top Height	(1)	no	1, 2, 3, 4, 5,	Sampling studies
Cloud Top Height	(1)	Imaging VIS and IR Sensors	1, 2, 3, 4, 5,	Sampling studies
Cloud Coverage	(1)	no	1, 2, 3, 4, 5	Sampling studies
Cloud optical thickness	(2)	no	2, 3, 4, 5	Development of retrieval methods
Cloud tracking (wind determination)	(1)	Imaging VIS and IR sensors on geostationary satellites	1	Sampling studies
Ice/water discrimination in clouds (raining clouds) (polarisation measurement necessary)	(1)	no	1	Sampling studies and test of method
Tropospheric aerosol layering	(1)	no	(Height of planetary boundary layer and tropopause), 2, 3,	Sampling studies, how often are aerosol layers and temperature coupled ?
Tropospheric aerosol layering	(1)	Temperature profilers (TOVS)	1, 2, 3, 4, 5	Sampling studies, Insertion into retrieval algorithm
Tropospheric aerosol layering	(1)	Multispectral Radiometers	(Contribution to radiation budget) 2, 3, 4, 5	Sampling studies
Tropospheric aerosol extinction coefficients, vertical profiles	(2) + (3)	no	(contr.. to radiation budget), 2, 3, 4, 5, (aerosol size distribution	Sampling studies, Dev. of retrieval methods, study of linkage between 0.7 and 10 micron
Tropospheric aerosol extinction coefficients, vertical profiles	(2) + (3)	Radiation budget packages (ERBE or CSR)	(radiation divergence), 2, 3, 4, 5	idem
Tropospheric aerosol extinction coefficients, vertical profiles	(2) + (3)	Radiometers for ground temperature	(ground temperature), 1, 2, 3, 4, 5	idem
Stratospheric aerosol layering	(1)	no	3, 4, 5	no
Stratospheric aerosol extinction coefficients, vertical profiles	(2) + (3)	no	3, 4, 5	no
Aerosol tracking	(1)	Imaging VIS and IR sensors on geostationary satellites	3, 4, 5, 6	no

Wavelength desired: (1) one wavelength at 0.7, 1.06 or 10 micrometer  
 (2) two or three wavelengths at 1.06 micrometer and at doubled and tripled frequency  
 (3) 10 micrometer

Area of Application: (1) Weather forecast  
 (2) Medium range climate/weather prediction  
 (3) Climate modelling (input data and data for verification)  
 (4) Climate modelling  
 (5) Atmospheric reserach  
 (6) Air pollution monitoring

Therefore, the resulting improvements using two frequencies compared to, or in combination with, passive measurements at different wavelengths need careful examination. In the case of aerosol measurements, the above-mentioned sampling problem is of less importance as the aerosol layers are generally homogeneous over horizontal scales of several kilometres.

#### (f) Radiation budget

The radiation received from the Sun is the primary energy source of the Earth-atmosphere system. The determination of radiation flux densities on a global scale is thus one of the most important climatological tasks. Moreover, the radiation-budget parameters are valuable indicators of possible climatic changes. To describe the energy fluxes completely, it is necessary to obtain the values of the radiative fluxes at the top of the atmosphere and at the ground, and data on the vertical distribution of the up and down-dwelling fluxes in the short-wave (solar) as well as in the long-wave (terrestrial) spectral ranges.

However, for the latter problem no direct measurements are presently available. To improve the indirect determination via model calculations of radiation fluxes within the atmosphere, it is thus necessary to improve the knowledge of the vertical profiles of the optically relevant parameters of the atmosphere. The most significant are the clouds. They strongly influence the radiation divergence in both spectral ranges, depending on their height and temperature as well as their optical and geometrical thicknesses. Furthermore, atmospheric radiation fields are influenced by mass distribution and optical properties of the aerosol particles, as well as by the vertical profiles of humidity and of minor constituents. The usefulness of lidar measurements for the determination of radiation fluxes therefore lies directly in the possibility of getting more accurate information on the vertical profiles of clouds and aerosol particles, as already outlined in the previous paragraphs.

#### (g) Conclusion

Table 3.3 summarises the potential and expected areas of application of a simple backscatter lidar. **It shows that such a system will be of particular value for the diagnosis of the atmosphere to improve weather forecasting and medium-range climate/weather prediction, for climate monitoring and for atmospheric research. It certainly constitutes a high-priority candidate for early space implementation, taking into account the few technological developments required and the expected scientific return.**

A DIAL lidar provides direct measurements of such meteorological variables as humidity, surface pressure, pressure and temperature profiles. A dual-frequency emission can be used for an integrated path differential absorption measurement. One frequency is chosen in a resonant absorption feature of the constituent under study (on line -  $P_{on}$ ), the second one being free of absorption (off line -  $P_{off}$ ). Differentiation of the ratio of the backscattered signals  $P$  at the two frequencies yields the local optical depth :

$$\partial \tau (z) = \frac{1}{2} \frac{\partial}{\partial z} \ln \frac{P_{on}(z)}{P_{off}(z)}$$

### 3.2 DIAL Lidar

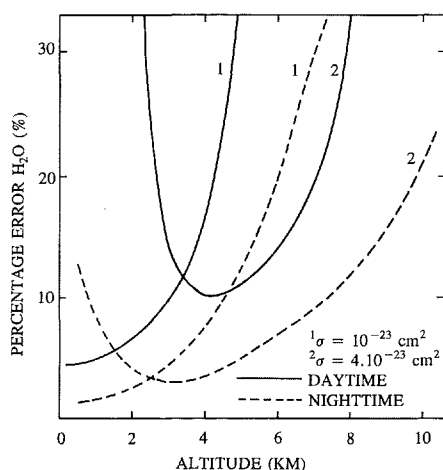


Figure 3.3. Uncertainty in water-vapour content as measured by a near-infrared DIAL system (0.5 J; 10 Hz; 1.25 m telescope; surface albedo 0.3). (From G. Megie, 1987)

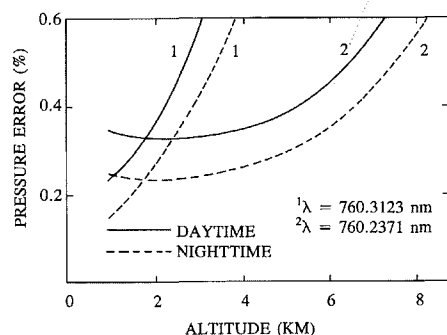


Figure 3.4. Uncertainty in DIAL pressure measurements using various oxygen absorption troughs in the near-infrared (0.5 J; 10 Hz; 1.25 m telescope; surface albedo 0.3). (From G. Megie, 1987)

An a-priori knowledge of the spectroscopic properties of the measured constituent can then lead to the determination of:

- its **number density profile**. This is the case for the humidity profile using absorption features in the near infrared (730 nm). Generally speaking, a DIAL lidar will be able to measure water-vapour profiles under nighttime and daytime conditions with a vertical resolution of better than 1 km and an horizontal resolution of between 100 and 250 km, compatible thus with the grid of most of the simulation models. Overall precision is better than 10 % over a 6 km altitude range. Furthermore, an appropriate choice of the emitted wavelengths can lead to higher resolution measurements (0.3 to 0.5 km) within the boundary layer;
- the **surface pressure and pressure profile** when using molecular oxygen as the absorber, assuming constant mixing with altitude and operating in the wings of the absorption lines. Measurements are performed in the A band near 760 nm with an overall accuracy of better than 0.2 % for the surface pressure and 0.4 % for the pressure profile up to 6 km for vertical and horizontal resolutions similar to those obtained for humidity measurements;
- the **temperature profile**, again using molecular oxygen but operating at the centre of a highly excited vibration line. Appropriate choice of the emitted frequencies leads to an overall accuracy of better than 1 K up to the tropopause level.

In addition, using the backscattered signal at the off frequency, all measurements attainable with a simple backscatter lidar, as referenced in the previous subsection, can also be performed.

DIAL measurements of **water-vapour profiles** will complement and enhance the capabilities of passive sensors related to weather forecasting and to the study of the radiative budget and the hydrological cycle. While passive H<sub>2</sub>O measuring sensors provide global coverage, they are somewhat restricted in resolution, especially in the lower tropospheric regions, including the planetary boundary layer. A DIAL lidar will provide range-resolved measurements, particularly between clouds, which will improve profile retrievals from passive sensors. They will also allow the determination of a vertical profile within the boundary layer (2 to 3 levels), thereby allowing a possible determination of averaged humidity fluxes and hence latent-heat fluxes, which play a major role in the radiative convective equilibrium of the lower troposphere over ocean surfaces.

The **pressure field** is of particular importance for weather prediction or for the study of atmospheric circulation. For example, surface pressure and 500 mb geopotential heights are used to describe mass motions in the atmosphere and to study the frontogenesis and further evolution of meteorological systems. The pressure profile can be used to specify both the temperature profile and the balanced wind, whereas the reciprocal, i.e. the determination of a pressure profile from a temperature profile, is only possible if a reference pressure height is determined. DIAL lidar provides the only remote-sensing technique for the measurement of both the surface pressure and the pressure profile. As already pointed out, the lack of an accurate pressure reference level presently prohibits the determination of pressure profiles from passive-sensor measurements of temperature profile. The DIAL pressure lidar will thus greatly enhance the scientific return from passive temperature sounding for determination of the mass field in the atmosphere.

The **temperature field** is obviously one of the basic atmospheric parameters required for meteorological and climate studies on all scales. Here, the DIAL lidar can provide a direct measurement of the temperature profile which does not require the use of inversion techniques. The vertical resolution can also be enhanced compared to passive sensors. However, a careful study should be made to determine the effective improvement that could be expected from such a system, compared with the combination of a backscattered lidar and passive sensors, as studied in the previous subsection. In any case, and as for the water-vapour profiling capacity, high-resolution measurement within the boundary layer will also provide an unique way of determining averaged sensible heat fluxes by measurement of horizontal and vertical temperature gradients.

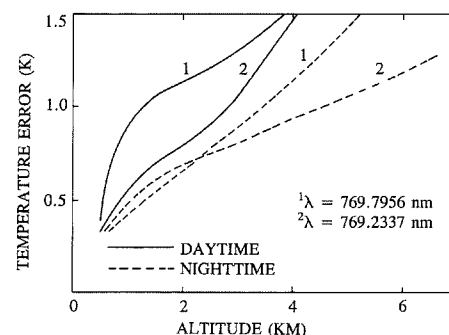
Compared with measurements performed with a simple backscatter lidar system, a DIAL lidar will additionally provide:

- Unique measurement capacity for surface pressure, pressure profiles in the troposphere and high-vertical-resolution measurements of humidity and temperature in the boundary layer.
- Complementary measurement capacity for humidity and temperature profiles in the troposphere and lower stratosphere.

Taking into account the additional complexity of the instrument (dual emission, tunability) **the DIAL lidar will constitute a very valuable step in the development of spaceborne lidars** and is an obvious **follow-on technical development to simple backscatter systems**. It constitutes a required complementary instrument for advanced weather forecasting, taking into account the determination of the pressure field and study of the global hydrological cycle and considering its potential for remote determination of averaged heat and humidity fluxes.

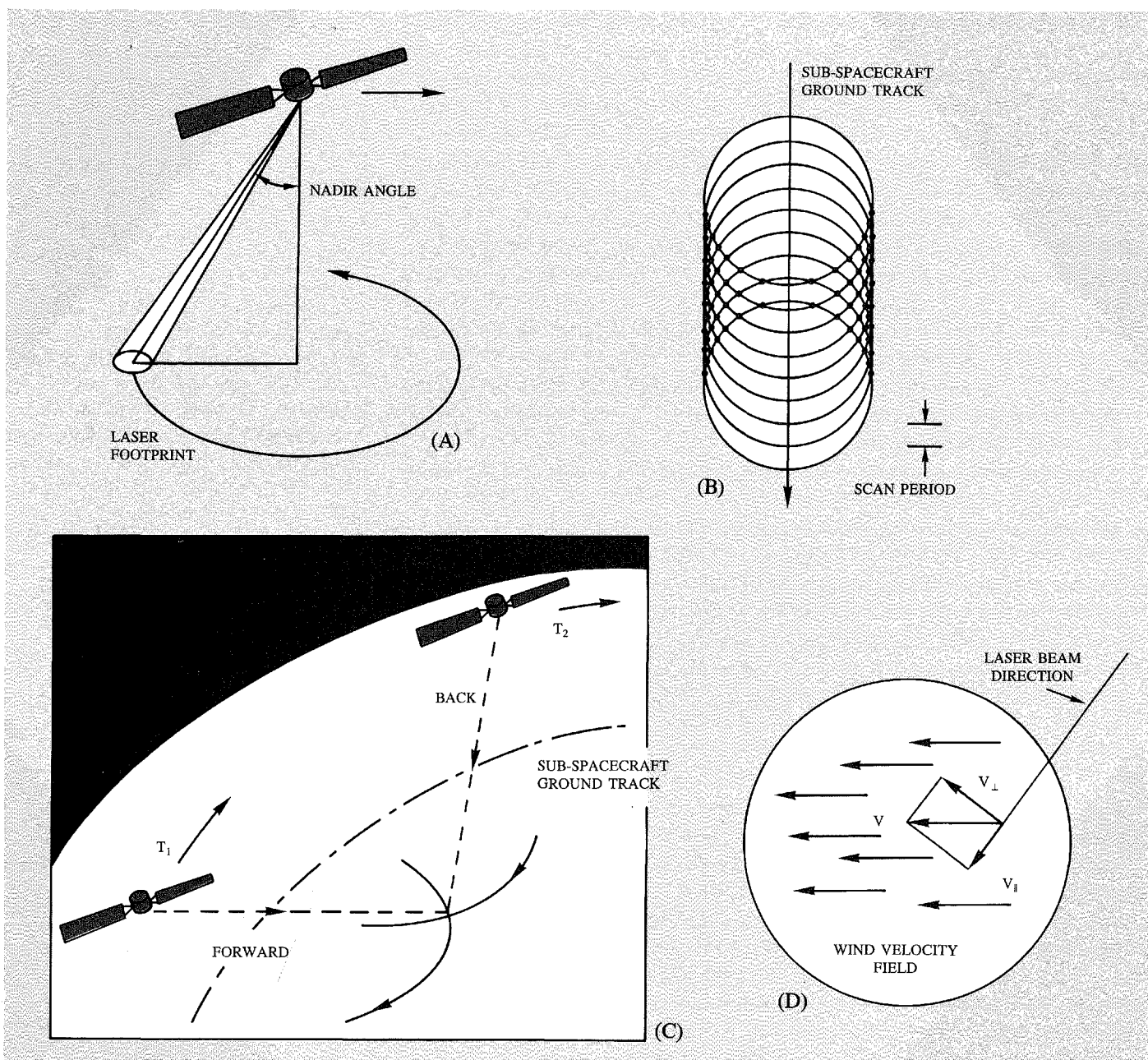
In a wind Doppler lidar, a small fraction of the incident laser-beam radiation is backscattered by naturally entrained aerosols so that the laser frequency is Doppler-shifted due to the air's motion. Since the process inherently measures the line-of-sight velocity component, scan techniques and processing algorithms must be employed to obtain the desired horizontal wind field. The combination of telescope scanning and spacecraft motion allows the same atmospheric volume to be seen from different viewing angles. The expected accuracy, from simulation models, for a spaceborne Doppler wind lidar can meet the measurement objectives of 1-2 m/sec throughout the troposphere. In comparison to other types of wind sensors, the pulsed coherent Doppler wind lidar can currently be considered the best candidate for space-based operation, taking into account its measurement heritage and technological readiness.

A wind coherent Doppler lidar, whether on a polar platform for global wind vector fields or on the Space Station for tropical wind profiles, will provide essential information for advancing numerical weather-prediction skills, furthering our knowledge of the large-scale atmosphere circulation and climate dynamics, and improving our understanding of hydrologic and bio-geochemical cycles. Numerical experiments performed by operational weather-prediction centres (e.g. the European Centre for Medium Range Weather Forecasts (ECMWF), the various National Meteorological Offices in Europe and the USA, and research laboratories) has indicated that wind profiles are the most important data sources for



**Figure 3.5. Uncertainty in DIAL temperature measurements using various oxygen-absorption lines in the near-infrared (0.5 J; 10 Hz; 1.25 m telescope; surface albedo 0.3). (From G. Megie, 1987)**

### 3.3 Doppler Wind Lidar



**Figure 3.6. Principle of wind determination with a spaceborne scanning Doppler lidar.**

- (a) Scan geometry
- (b) Scan pattern
- (c) Forward and backward views of the same area for wind-component retrieval
- (d) Wind vector determination by means of forward and backward observations

weather-prediction improvement. This improvement will occur through the enhancement of the coverage and data quality in areas already served by conventional radiosondes, and through the extension of the coverage of high-quality wind profiles to the sparsely instrumented oceanic and Southern Hemisphere areas.

The increased use of global wind vectors in numerical-prediction models offers perhaps the greatest potential for increased accuracy in operational forecasting. As a matter of fact, more detailed temperature sounding are held to be of less importance, especially in low-latitude regions (tropics), where direct observations will be of particular importance, since pressure patterns cannot be used to calcu-

Table 3.4. Characteristics of various spaceborne wind sensors

	Resolution					
Instrument	Horizontal (km)	Vertical (km)	Temporal (h)	Accuracy (m/s)	Coverage	Limitations
<i>Passive</i>						
High-Resolution Doppler Imagers	125	4	24	<5	Middle/upper troposphere: Stratosphere	Low resolution and accuracy; no tropospheric coverage
Electro-optical Modulation Correlators	150	5	24	<5	Stratosphere and mesosphere	Low resolution and accuracy; no tropospheric coverage
Cloud-Motion Imagers	20—50	none	0.1 to 1	2	10 000 km <sup>2</sup>	No global coverage No vertical profiles
<i>Active</i>						
Doppler Radars	10	0.2	<0.1	1	In precipitating systems: Regional	Excessive size and power consumption
Scatterometers	25	none	12	±10% ±20%	Global oceanic surface	Low accuracy No vertical profiles
Doppler Lidars	100	0.2 to 1	12	1 to 3	Global troposphere	Immature technology No coverage in cloudy regions

late atmospheric motion, and since there are too few observing stations. The tropics are of particular interest, since much of the global energy input to the atmosphere occurs there. Even less understood are the teleconnections between large-scale atmospheric processes in the mid latitudes and anomalies in the tropics (El Niño episodes). Along with the increasing importance of having global measurements for successful medium-range (3 to 10 days) and short-range (1 to 2 days) numerical weather forecasting, the importance of obtaining mesoscale observations for very short-term (3 to 18 hours) forecasts is becoming increasingly evident. The conventional sounding network has difficulty resolving the mesoscale features and, as a consequence, the initial conditions for operational numerical models fail to capture important details necessary for a successful forecast. For the mesoscale studies, 100km-horizontal-resolution soundings of wind, temperature and moisture, coincident in time and space, are required. The accuracies should be of the order of  $1 \text{ ms}^{-1}$  for the horizontal wind components, and 1 K for temperature and dew point.

A recent study shows that for short scales (about 2000 km), satellite winds with a component accuracy of  $2.7 \text{ ms}^{-1}$  at 500 mb and  $5.0 \text{ ms}^{-1}$  at 250 mb would bring the combined accuracy of winds and satellite temperature over the ocean to the same level globally that the current Rawinsonde network has over land in the Northern Hemisphere. For longer scales (8000 km), the required accuracies are  $1.0 \text{ ms}^{-1}$  and  $2.2 \text{ ms}^{-1}$ , respectively.

The Doppler wind lidar will thus provide a unique measurement capability for tropospheric winds on a global scale with accuracy and spatial resolution compatible with operational meteorology and climatology requirements. Taking into

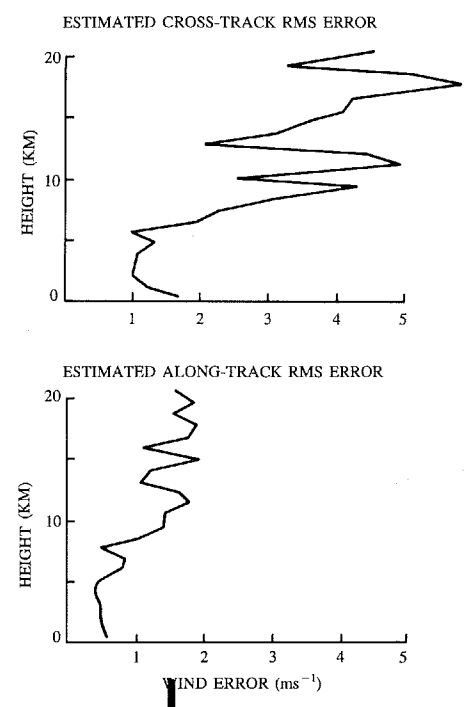


Figure 3.7. Performance simulation of along-track and across-track wind-measurement accuracy

account the instrument complexity and the requirements for extensive studies of the atmospheric backscatter at 10 micron (GLOBE programme) to support the viability of the concept, the Doppler wind lidar is certainly a **high priority candidate for a second phase implementation in space**, provided that the necessary development is undertaken as soon as possible.

### 3.4 Other Lidar Systems

The lidar systems considered so far are mainly devoted to applications in the fields of meteorology, climatology and atmospheric research. Given today's requirements in the environmental sciences, they certainly constitute the highest priority elements of a lidar space programme. However other lidar systems may also have potential spaceborne applications, and interest could increase as our knowledge of atmospheric phenomena progresses.

As outlined in Chapter 2, a major challenge in environmental studies will be to acquire global information on the concentration of a number of trace gases, which play a determining role as sources of chemically active species and/or as potential agents in the modification of the Earth radiation budget: methane, carbon dioxide, nitrogen oxides, chlorine compounds, etc. Most satellite experiments to detect and measure trace gases in the atmosphere have so far been restricted to stratospheric observations, where long-path absorption techniques can be used. Potential applications of spaceborne lidar systems to tropospheric and surface studies in this context will include:

- UV DIAL lidar for ozone monitoring in the stratosphere where the main effect of ozone reduction by chlorine related catalytic cycles is to be expected (30-50 km). However, it seems at present that the detection of trends related to anthropogenic activities can be achieved by a combination of passive sensors such as the SBUV instrument, and a network of ground-based lidar stations for continuous validation.
- DIAL CO<sub>2</sub> lidar, with heterodyne detection for increased sensitivity, for the measurement of the total content of tropospheric species using the reflection of the Earth's surface and/or from cloud tops. Altitude profiles can also be obtained with the use of pulsed laser sources or continuous-wave (cw) laser sources which can be tuned throughout absorption features of the constituents of interest.
- UV/Visible lidar fluorosensor for investigations of the terrestrial and aquatic biomasses, water and land pollution or mineral resources. This technique relies on the analysis of the induced fluorescence spectra of absorbing substances or pigments (e.g. chlorophyll) following a short laser excitation pulse.

All of these systems have already been operated on the ground or on aircraft. Applications have thus mainly been related to local and regional observations. Nevertheless, their potential extension towards more global monitoring using spaceborne platforms might also have to be considered in the future.

### 3.5 Laser Altimeter and Ranging

Laser ranging and altimetry can provide accurate measurements of distances from a reference height – the satellite orbital height – to precise locations on the Earth's surface. It can improve our understanding and knowledge of many pro-



cesses and phenomena in the Earth sciences, as discussed in Chapter 2, such as geodesy, geodynamics, ice dynamics, land topography, and Earth resources.

To fulfil the observational needs, two separate instruments of differing complexity can be considered for spaceborne applications:

- (i) a laser ranging system for accurate point positioning in geodynamics, and
- (ii) a laser altimeter for altimetry measurements over land, oceans and ice.

Laser ranging (or inverted laser) from space would replace, or enhance the capability of, present ground-based laser ranging systems (SLR's).

For centimetre-accuracy measurements, a single-wavelength nanosecond pulse laser is sufficient, while for subcentimetre accuracy it has been shown theoretically that a dual-wavelength picosecond laser is required to compensate for the atmospheric propagation effects (beam refraction) that limit single-wavelength ranging to about one centimetre precision.

The main objective in geodynamics is to determine the relative displacement of specific points on the Earth with centimetre or subcentimetre accuracy. This is needed specifically near fault zones, for earthquake monitoring, or for understanding the forces that drive continental motion and plate deformation. The operational requirements of geodynamics dictate the establishment of a reference grid with local to continental scale. So far laser tracking to such high-altitude satellites as LAGEOS or STARLETTE has been performed from a number of ground-based stations with measurement accuracies of a few centimetres. However, because of the high operational costs involved and the time-consuming operating procedures, these observations have been limited to a small number of sites. The measurement precision achievable with advanced SLR systems (1-2 cm) is superior to that of currently planned radio-frequency point positioning systems, thanks largely to the insensitivity of the laser light to atmospheric water vapour, which severely limits radio-frequency precision.

The argument for having a spaceborne laser ranging system is that the present network of ground-based SLR systems lacks uniformity and density, and a greater density of sites is not conceivable considering the time, cost and volume of data involved. The use of laser ranging from satellite to ground-based reflectors would instead provide global coverage and unique subcentimetre resolution.

At the present time, however, a laser ranging system cannot be considered a strong candidate for space implementation, since the cost in terms of technical complexity and instrument development requirements is very high in relation to the scientific return. This is reinforced by the fact that alternative microwave techniques, which have been considered and discussed at several ESA remote-sensing workshops (see, for example, ESA SP-1080), can provide adequate scientific return for much less technological effort.

The **laser altimeter**, primarily for ice and land applications, can be considered an extension of the backscattering lidar instrument. As opposed to ranging applications where centimetre or subcentimetre accuracies are needed, the spatial resolutions required from laser altimeters (vertical and horizontal) pose considerably fewer technology problems and make it possible to derive the instrument from the backscattering lidar. The main characteristics of a laser altimeter are: the small diffraction-limited footprint (proportional to the laser wavelength), which permits topographic mapping of ice sheets, terrain, forestry or waters with high spatial resolution; the insensitivity to speckles, since direct detection can be successfully employed with a visible-wavelength laser; high single-pulse measurement accuracy,

since in principle no averaging is required; and the insensitivity of beam propagation to atmospheric water vapour.

The present active microwave instrument package for the ERS-1 satellite consists of a high-resolution imaging instrument (SAR) and a microwave altimeter (RA). A precise range and range rate instrument (PRARE), a microwave sounder and laser retroreflectors are employed for accurate orbit determination (10 cm absolute). They also provide correction for atmospheric propagation errors which, at microwave frequency, can be several decimetres. The radar altimeter can achieve a 2 m absolute vertical resolution over the oceans, but its large geometrical footprint of 20 km, or in the pulse-limited mode of about 2 km, cannot detect small-scale undulations and so errors can occur, especially over land and ice. The laser altimeter can provide measurements with higher accuracy and spatial resolution than radar altimeters, but only under non-precipitating conditions. In overcast areas, the effects of clouds on measurement accuracy must be assessed, as well as the beam sampling problem.

On technology grounds, the **laser altimeter** can be considered a **realistic instrument** which can be deployed in space by the mid 90's, ideally in conjunction with a microwave altimeter, since the combination of the two instruments is expected to lead to an all-weather instrument package providing high spatial resolution and accuracy.

# Chapter 4

## Lidar Systems

In the previous chapters, the observational requirements for improved meteorology, climatology and solid-Earth research have been presented and discussed. It has also been shown how lidar instruments in space, thanks to their unique properties, can contribute substantially to our understanding of the Earth system. Their complementarity with existing or planned passive or active microwave or optical instruments has also been emphasised.

Lidar is not an unique instrument with all measurements capabilities being addressed by a single system. Each lidar sensor has its specific characteristics and requires specific technology development for space implementation. The complexity of the various subsystems varies greatly from one lidar system to the other, and the purpose of this chapter is to provide detailed information on each of the lidar instruments identified in Chapter 3: backscattering lidar, DIAL lidar, Doppler wind lidar, laser ranger and altimeter. For each of these, the state of the art in lidar development will be briefly reviewed and present day measurement capabilities illustrated. The key subsystems will then be described to allow future identification of technological developments required for spaceborne instruments. To follow the classification adopted in the previous chapter, the backscatter lidar will be described in Section 4.1, including a complete description of all lidar subsystems: laser transmitter, receiver and data acquisition and storage systems. In the following subsections, DIAL lidar, Doppler wind lidar, laser ranger and altimeter will be described with emphasis on the major differences with respect to the backscattering lidar, in order to avoid repetition. The description of the various laser sources (Nd-YAG laser, vibronic crystal laser, CO<sub>2</sub> laser) has been split between the three lidar subsections 4.1 (backscatter lidar - Nd-YAG laser), 4.2 (DIAL lidar - vibronic crystal lasers), 4.3 (Doppler wind lidar - CO<sub>2</sub> laser) to emphasise their main fields of application. This division is somewhat arbitrary as some of these laser sources might have applications in several lidar systems.

In Chapters 2 and 3 it has been shown that a spaceborne backscattering lidar can substantially improve our knowledge and understanding of many phenomena and observational parameters in atmospheric science and application areas.

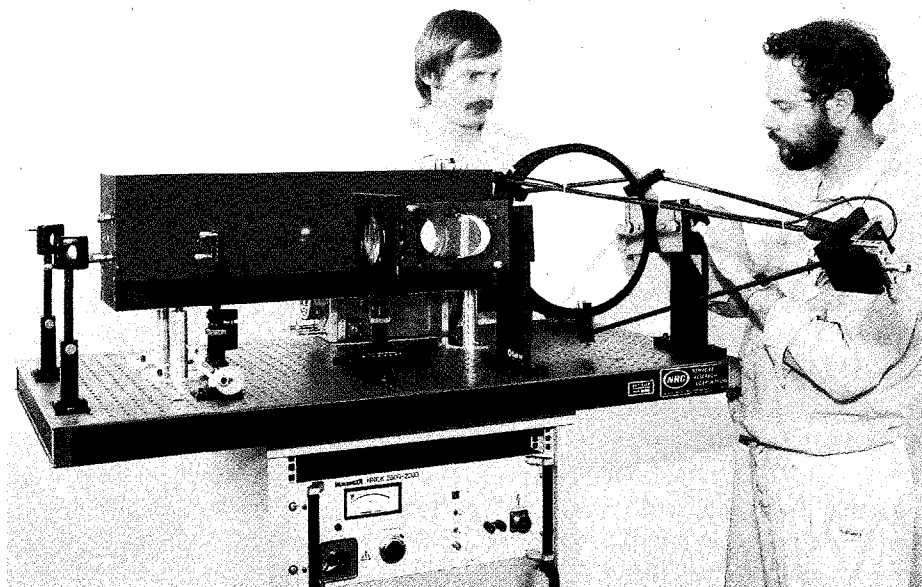
Technologically, the backscattering lidar is the least complex of the various lidar considered, requiring relatively few technological developments and also being the least demanding for spacecraft accommodation. In fact its power, data storage and rate, pointing and attitude requirements are the least demanding of the various spaceborne lidar candidates and are within the capabilities of forthcoming platforms such as the Eureka retrievable platform, or the Columbus polar and/or coorbiting platforms.

Since the first observation of atmospheric aerosols with a ruby laser radar (Fiocco and Smullin, 1963) many more refined instruments have been built and operated from the ground, mobile vans and aircraft, in Europe as well as in the USA. Today there are many projects to fly autonomous and automated backscattering lidars, such as the French-Soviet experiment on MIR, or the French-German initiative on Shuttle, or the US "LITE" experiment, all scheduled for the early 1990's.

To illustrate the potential of a backscattering lidar for multidimensional retrievals of atmosphere structure, Figure 4.2 shows a two-dimensional, i.e. horizontal and vertical, distance plot of the signal backscattered from the atmosphere at

### 4.1 Backscattering Lidar

**Figure 4.1.** Laboratory model of a backscattering lidar developed jointly by Battelle (Frankfurt) and CISE (Milan) under the ESA Technology Development Programme. The laser transmitter, the telescope and the photomultiplier tube in the metal housing can be seen



1 micron. This data was obtained by DFVLR (Germany) during an airborne lidar campaign in 1984 (Alex, Dialex). What is important to observe in this figure is the presence of the planetary boundary layer (and then of the temperature inversion layer) at a height varying from 400 to 600 m above the ground. Such data are of particular importance, as already emphasised, for both meteorology and climatology, and show the uniqueness of the lidar instrument for providing such information. Passive sensors are not capable of determining boundary layer parameters, while very clearly this can be read by the lidar signature due to the jump in the signal intensity that results from the change of aerosol concentration.

The backscattering lidar system, like all lidar instruments, consists of three main units: the Transmitter, the Receiver including the detection package, and the Data Processing and Transmission Package (Fig. 3.1).

#### (a) Transmitter

The most important component of the transmitter is the laser. Table 4.1 provides a summary of performance specifications for the laser transmitter. For back-

**Table 4.1.** Typical performance specifications for the transmitter laser of a backscattering lidar

Wavelength	0.5—1 micron
Average pulse power	1—5 W
Pulse energy stability	2%
Pulse beam divergence (FOV)	100 $\mu$ rad
Pointing accuracy	better than 0.5 mrad
Pulse duration	shorter than 100 ns
Beam polarisation	linear, preferable
Laser efficiency	1—2% preferable
Laser lifetime	3 yr
Laser emission line width	0.1 $\text{cm}^{-1}$ or shorter, preferably
Frequency stability	0.1 $\text{cm}^{-1}$

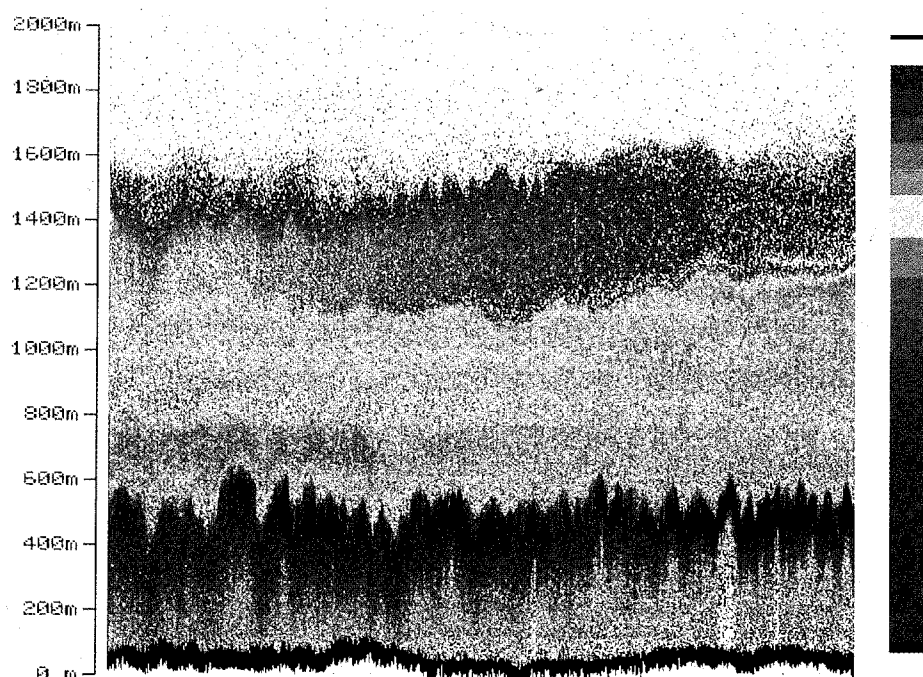
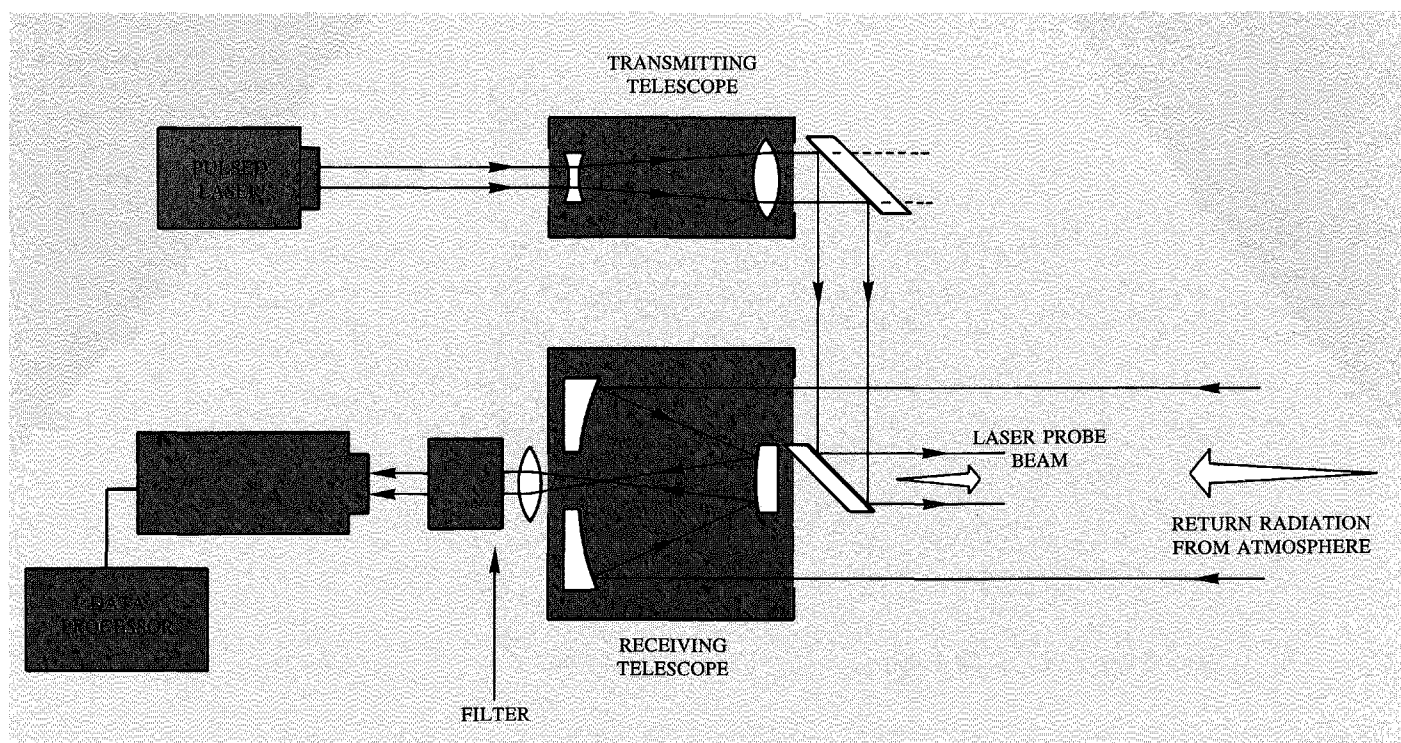


Figure 4.2. Atmospheric density plot as a function of the height above the ground (Courtesy of U. Renger, DFVLR)

scattering applications, the laser should have the following performance:

- **Laser energy;** a value ranging from approximatively 0.1 to about 1 J can be considered adequate. Strong scatterers, such as clouds, can be detected with little energy (about 10 mJ from a 800 km orbit), while rather higher energies are required for weak scatterers, such as high-altitude aerosols. However, the spatial-resolution requirements are generally different for the various observations and this leads to different requirements in terms of laser repetition rate, which means that the transmitted average power is not much different for the various observations.
- **Repetition frequency;** this is generally a compromise between required horizontal resolution and maximum available power. Values ranging from a few to some hundreds of Hz might be needed.
- **Pulse duration;** this sets the limit to the achievable vertical resolution. A pulse length of few hundred nanoseconds or less would permit to obtain adequate vertical resolution, limited only by the bandwidth of the detection system.
- **Lifetime;** the laser lifetime is a crucial factor since it mainly determines the mission duration. A mission dedicated to Earth observation on a polar or a coorbiting platform would require a laser lifetime of at least 3 years.
- **Laser beam spectral and spatial characteristics;** although the beam characteristics are not critical for backscattering applications, because the amplitude and not the phase of the return signal is detected, a high spatial beam quality is required to reduce optical damage problems. Furthermore, a narrow band emission spectrum would be advantageous to filter out the solar background radiation for day-time measurements.
- **Laser wavelength;** the choice of wavelength for backscattering applications depends on many factors. Since clouds and aerosols are to be measured, it is important that the operating wavelength be higher than approximatively 0.35



**Figure 4.3. Schematic of a backscattering lidar system.** The light backscattered from clouds or aerosols is collected by the receiver telescope and directed towards the detection system. The electrical output signal generated is then processed and transmitted to the ground or stored for spatial averaging or later data transmission

microns, in order that particulate scattering (Mie) dominates molecular scattering (Rayleigh molecular scattering increases with the square of the frequency). For the near-visible range, detector sensitivity considerations lead to the requirement that the wavelength be below about 0.8 micron, since detectors are available (photomultipliers) with quantum efficiencies of up to 20 % (at around 0.5 micron). In addition to the near-visible region, the infrared region at around 10 microns – where molecular scattering can be completely neglected – is also of interest, since heterodyne detectors with 40% quantum efficiency can be used efficiently.

Suitable laser candidates for backscattering-lidar applications from space are described below.

#### *Nd-based lasers*

Nd-YAG laser is the most widely used solid-state laser. Nd-YAG laser technology is well developed both in and outside Europe, and applications can be found in science, industry, biology, medicine, etc. Today flight-qualified Nd-YAG laser range finders are commercially available with outstanding performance and reliability. This laser crystal has excellent mechanical and thermal properties, and high average and peak power can be obtained.

Nd-YAG laser emits radiation centred at 1.064 micron which can be tuned over about  $5 \text{ cm}^{-1}$ . Laser pumping can be performed with flash lamps, or for low-power applications also with diode lasers. Laser systems with energies up to 100's J, average power of several 100's W, and efficiencies of 1-2% are commercially available.

Diode-pumped Nd-YAG lasers are experiencing very rapid growth. A 2 mJ Nd-YAG laser with a 100 Hz repetition frequency is already commercially available

and experimental devices with output powers of more than 20 W in a 200  $\mu\text{s}$  long pulse have been recently reported, and higher power devices are expected in the near future. Diode laser pumping can lead to Nd-YAG lasers with single longitudinal and transverse mode operation. The overall pumping efficiency (wall plug to Nd-YAG emission) is typically 5-8%, and a lifetime of several years is assumed to be possible.

The Nd-Glass laser operates at slightly shorter wavelength than Nd-YAG, i.e. at 1.059 micron. The Nd ions in the glass host give rise to a quite different active material with a lower specific gain than YAG (similar to the specific gain of Alexandrite), but with a higher gain bandwidth. This leads to higher energy-storage capabilities and a higher tuning range (about 150  $\text{cm}^{-1}$ ). Nd-Glass has a thermal conductivity about one order of magnitude lower than that of Nd-YAG, and this limits the extractable average power to lower values than in the case of Nd-YAG. However, recent laser pumping with slab configurations has shown that the thermal effects can be considerably reduced, allowing high extracted average power for Nd-Glass also.

Nd<sup>3+</sup> ions lase efficiently in various other crystal hosts, such as Nd:YLF, Nd:BEL, Nd:Cr:GSGG, giving rise to numerous laser transitions between 1 and 1.4 microns. These, and other new solid-state lasers (notably Ho:YAG at 2.1 microns) are being investigated today and in the near future could well replace the more developed and better-known lasers recommended here for spaceborne lidar applications.

#### *Tunable vibronic and CO<sub>2</sub> lasers*

These two laser sources will be described in some detail in the following subsections on DIAL and Doppler wind lidar. It should however be emphasised once more that they might represent adequate sources for a backscatter lidar (see Chapter 5).

#### *Transmitter optics*

The transmission optics has to transport the beam from the laser exit mirror to outer space and ensure sufficient optical efficiency for the receiver. It consists of an expansion telescope plus additional tilting mirrors. The telescope is needed to reduce the transmitted beam divergence below the receiver telescope field of view, while the tilting mirrors are required to transmit the beam coaxially with the receiver telescope's optical axis.

#### **(b) Receiver and Data Acquisition and Storage System**

The receiver collects the backscattered light and generates a corresponding electric signal, which is subsequently processed and stored, or transmitted. The receiver is comprised of the receiver optics, and the signal detection and processing electronics.

#### *Receiver optics*

The receiver optics consist of the receiver telescope, and additional optics to transport and eventually filter the received light beam before detection.

The telescope consists of a large primary collecting mirror (50 -130 cm diameter) and a smaller secondary mirror. It is a rather conventional device, and for spaceborne applications it should be light in weight, insensitive to misalign-

**Table 4.2. Characteristics of three telescope designs**

Feature	Newtonian	Cassegrain	Dall-Kirkham
Fabrication difficulty			
Primary mirror	Moderately difficult (paraboloid)	Moderately difficult (paraboloid)	Moderately difficult (oblate spheroid)
Secondary mirror	Moderately simple (optical flat)	Extremely difficult (hyperboloid)	Extremely simple (convex sphere)
Centre obscuration	Most	Intermediate	Least
Overall telescope weight	Most (added structure required to support detector at front of telescope tube)	Intermediate	Least (telescope can be slightly shorter than Cassegrain)
Ease of alignment	Extremely simple	Extremely difficult	Relatively simple
Sensitivity to alignment	Very insensitive	Very sensitive	Relatively insensitive
Ease of mounting on pallet	Most difficult (detector must be supported at front of telescope tube; raises centre of gravity)	Fairly simple (center of gravity near pallet floor)	Fairly simple (center of gravity near pallet floor)
Ease of light shielding	Poorest	Very good	Best
Control of effective focal length	Minimal (governed solely by focal length of primary)	Good (provides moderately broad amplification range)	Excellent (provides extensive amplification range)

ment, and of sufficient optical quality. Many studies have already been performed to determine the optimum combination for space applications. Table 4.2 summarises the main characteristics of three telescope designs for a spaceborne lidar. Each of these has both advantages and disadvantages in terms of fabrication difficulties, ease of alignment or sensitivity to misalignment, etc.

The direction of arrival of the received beam is offset from the direction of the telescope line of sight by an angle that is caused by the overall motion of the scanner (telescope scanning + spacecraft translation) during the time of flight of the laser pulse. This angle, generally referred to as the overall lag angle, is made up of three contributions: the lag angle, the image motion, and the point-ahead angle. The lag angle is the angle through which the telescope moves during the sending and receiving of the backscattered signal; this is independent of the orbital height and of the order of 1 mrad. The image motion (sometimes also referred to as the lag angle) is the angle of telescope rotation during the time the backscattered signal is being received; this angle is of the order of 0.002 mrad. The point-ahead angle is caused by the translation of the spacecraft during the sending and receiving of the backscattered signal; this is about 0.004 mrad for a ground speed of 6.5 km/s.

Compensation of the lag angle for the backscattering lidar is rather easy to accomplish because it is practically constant and larger (1 mrad) than the receiver telescope FOV, the other pointing-error contribution; i.e. the image motion and the point-ahead angle are much smaller and can therefore be neglected.



### Scanning capacity

Without a beam-scanning facility, the area of the Earth observed during a single orbit would be limited to a very narrow region following the sub-satellite track. Many applications, particularly the more sophisticated ones that will be addressed by second-generation space lidars, will require coverage of a wide swath around the sub-satellite track. The requirements will vary for different applications, from correction for spacecraft/telescope pointing errors, to cross-track (zig-zag) scan, or conical scan strategies, and accurate location of specific ground targets (retro-reflectors/inverted lidars). These requirements can be met, bearing in mind the the scientific requirements, maximum laser pulse repetition rate and total power demand, by scanning the transmit laser beam together with the receive telescope across the sub-satellite track in a suitable scan pattern. If, for example, one wants to obtain half-Earth coverage in one orbit, then for a spacecraft orbital height of 800 km, a scanning angle of  $17^\circ$  is required, with a resulting ground track width of 500 km. If we take a scan period of 6 s, then the spacing of the grid points on the ground will be 26 km. This beam sampling is a characteristic of the lidar instru-

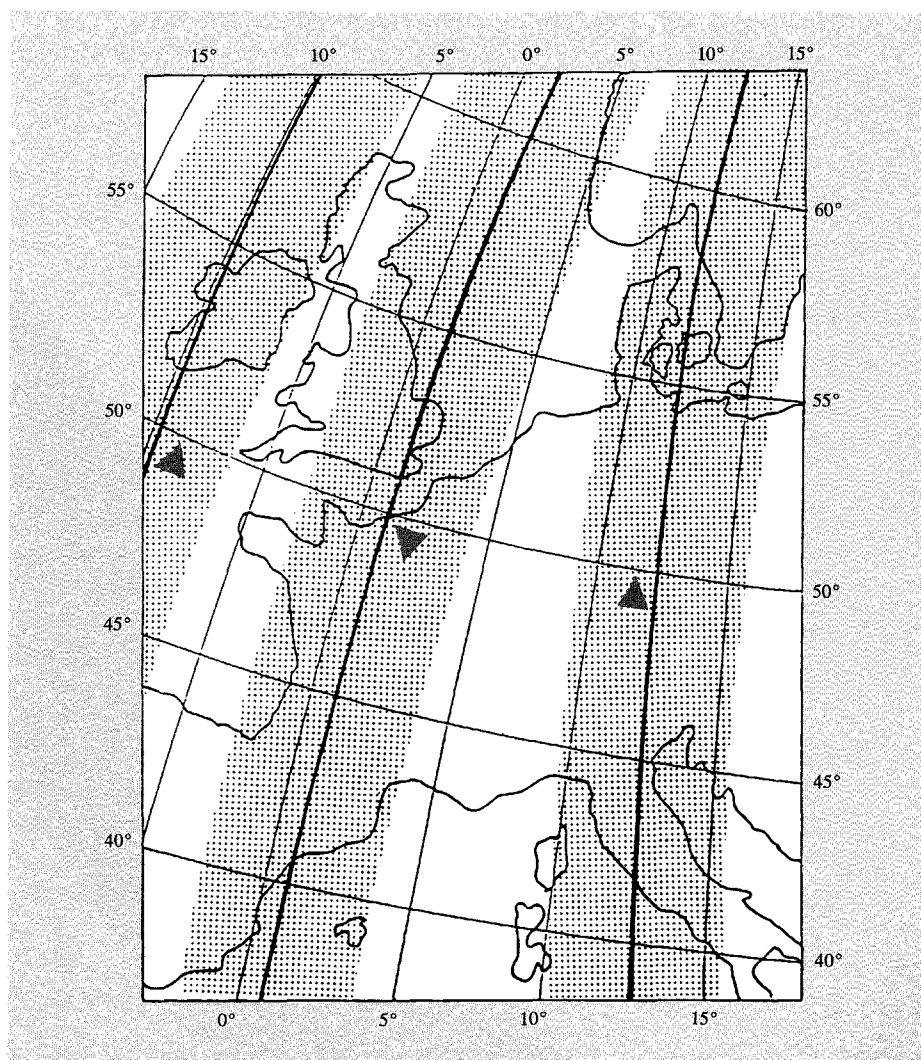


Figure 4.4. Ground coverage produced with a linearly scanning telescope for an orbiting lidar at 800 km altitude (scan angle  $17^\circ$ , scan period 6 s)

ment, and for certain cases this might not be desirable (see Chapter 3); this problem needs to be addressed for the application areas envisaged. However, the grid spacing can be varied by changing the laser repetition rate (if possible), scanning angle, or scan period. It is thus a trade-off between the scientific or application requirements and the technological implications.

Independent scanners for the transmitter and receiver telescope lead to a rather complex design, so various scanning designs which use the same optical components for scanning have been considered:

- (i) conical scan with a rotating telescope
- (i) linear scan with swinging telescope.

#### *Spatial and spectral filtering*

Spectral and spatial filtering can be implemented in the receiver channel to reduce the background radiation and increase the signal-to-noise ratio. Spatial filtering can be accomplished with an aperture that acts as a reducer of the receiver FOV; the spectral filtering can be accomplished using interference filters or, for higher contrast, with high-resolution interferometers.

#### *Detection*

Basically, three technologies are available for photon detection: avalanche photodiodes, photomultipliers and microchannel-plate photomultipliers.

Avalanche photodiodes are rugged, compact devices with a high intrinsic gain comparable to that of a photomultiplier ( $10^6$ ). However, the detection performance can degrade considerably with the low-noise, 10 MHz bandwidth amplifiers typically needed for lidar applications. The dynamic range achievable and the recovery time from overload require further study.

Photomultipliers (PMTs) are high-gain, high-quantum-efficiency photon detectors. The spectral range of PMTs extends from the UV, visible region up to about 1 micron, with an efficiency of 1-3 % at 1 micron and 10-20 % at shorter wavelengths. PMTs have been employed successfully in ground and airborne lidars, in both photon-counting and high-frequency analogue amplification mode: photon counting was used for weak upper atmosphere scattering (above 20 km), and analogue amplification for measurements in the lower atmosphere (below 20 km).

Microchannel-plate photomultipliers can provide very fast photon counting. They are in fact the most suitable photon detectors for measuring the weak back-scattered signals from the highest altitudes. A drawback is the large time constant of these devices, which renders fast gain switching and recovery from overload difficult, probably making analogue processing necessary.

#### *Data processing, storage and downlinking*

A fast (10-20 MHz) sampling rate is necessary for analogue signal processing when using a photodiode or photomultiplier detection system; a microchannel-plate photon counting regime (for high altitude only) would require an even faster counter (1 GHz). For real-time correction of data from passive sensors flown on the same spacecraft, fast and powerful digital processing of the backscattering data is necessary to allow re-programming to optimise the feedback algorithms.

The requisite data rate can be estimated with the following formula:

$$\text{Rate} = B \cdot S \cdot H \cdot T \quad (\text{bit/s})$$

with B the number of bits and S the sampling rate of the analogue-to-digital con-

**Table 4.3. Backscattering lidar instrument summary characteristics**

Estimated size*	0.5–0.7 m <sup>3</sup>
Estimated mass	100–150 kg
Estimated power	300–400 W
Estimated data rate (raw)	<400 kbit/s
Viewing requirements	Cross-track, 500 km swath (250 km each side)
Pointing stability	Non-critical
Pointing accuracy	1/30° roll, 1/10° in pitch and yaw

\* Assuming a conservative approach with flash-lamp-pumped Nd-YAG laser operating on both fundamental and second harmonic

verter,  $H$  the repetition rate, and  $T$  the data acquisition time. For:  $B = 12$ ,  $S = 10$  MHz,  $H = 10$  Hz, and  $T = 300$  s, the Rate = 400 kbit/s including housekeeping for additional information such as laser energy, amplifier setting, scanner position, etc. The onboard data acquisition/signal processing, feedback, storage, and downlink requirements are considerable compared with traditional spaceborne instruments, but are modest when compared with the requirements of a SAR radar instrument, for example, and the transmission capabilities of the envisaged European Data-Relay Satellite (DRS).

The orbital period of a spacecraft at an altitude of 800 km is about 100 min, so that the number of bits generated per orbit is  $400000 \times 100 \times 60 = 2.4 \times 10^9$  bits, and this gives the storage capacity required. The downlink rate will be at most 400 kbit/s and can be reduced significantly if some onboard processing is performed.

Table 4.3 gives an estimate of mass and power requirements for the backscattering lidar. These estimates, although rather conservative since based on today's technology, are well within the capabilities of future mission opportunities for Earth observation.

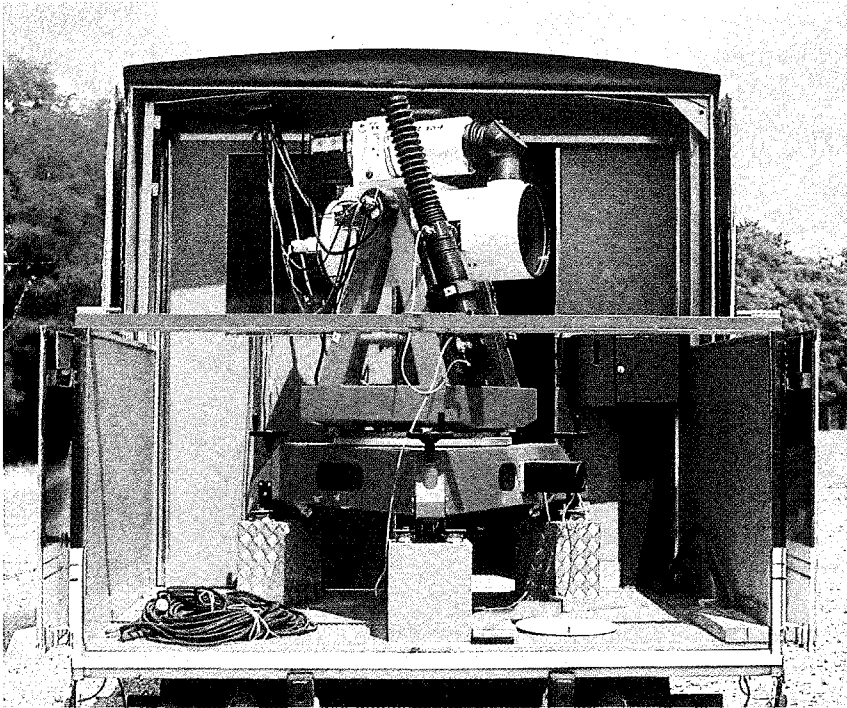
DIAL systems have been used for many years in ground-based stations, fixed and mobile, and flown on aircraft for pollution monitoring and water-vapour and pressure profiling in the troposphere. Today many programmes are under way to fly autonomous, automated DIAL lidars; for example, the French LEANDRE project (water vapour, temperature, pressure measurements sponsored by CNRS-CNES and INSU), the German (DFVLR) project for airborne water-vapour measurements, or the NASA-CNES initiative to fly an autonomous DIAL system onboard a high altitude ER-2 aircraft (LASE project).

The DIAL lidar instrument (Fig. 4.8) can be considered as an evolution of the basic backscattering lidar, which employs two transmitter lasers (or a laser which transmits two separate beams of different wavelengths with a well-defined temporal and spectral relationship) rather than one.

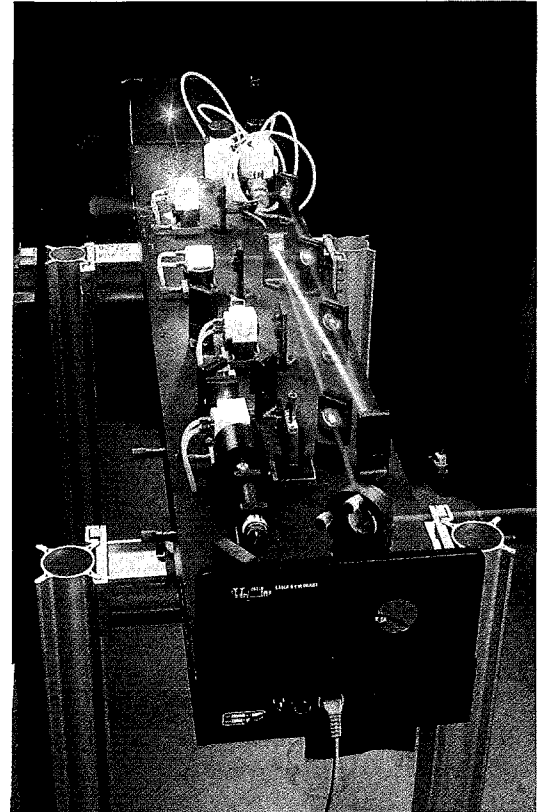
In addition to the need for a tunable laser source, there are specific requirements in terms of:

- wavelength selection and positioning
- spectral narrowing
- two-wavelength emission
- Doppler shift monitoring.

## 4.2 DIAL Lidar



4.5.



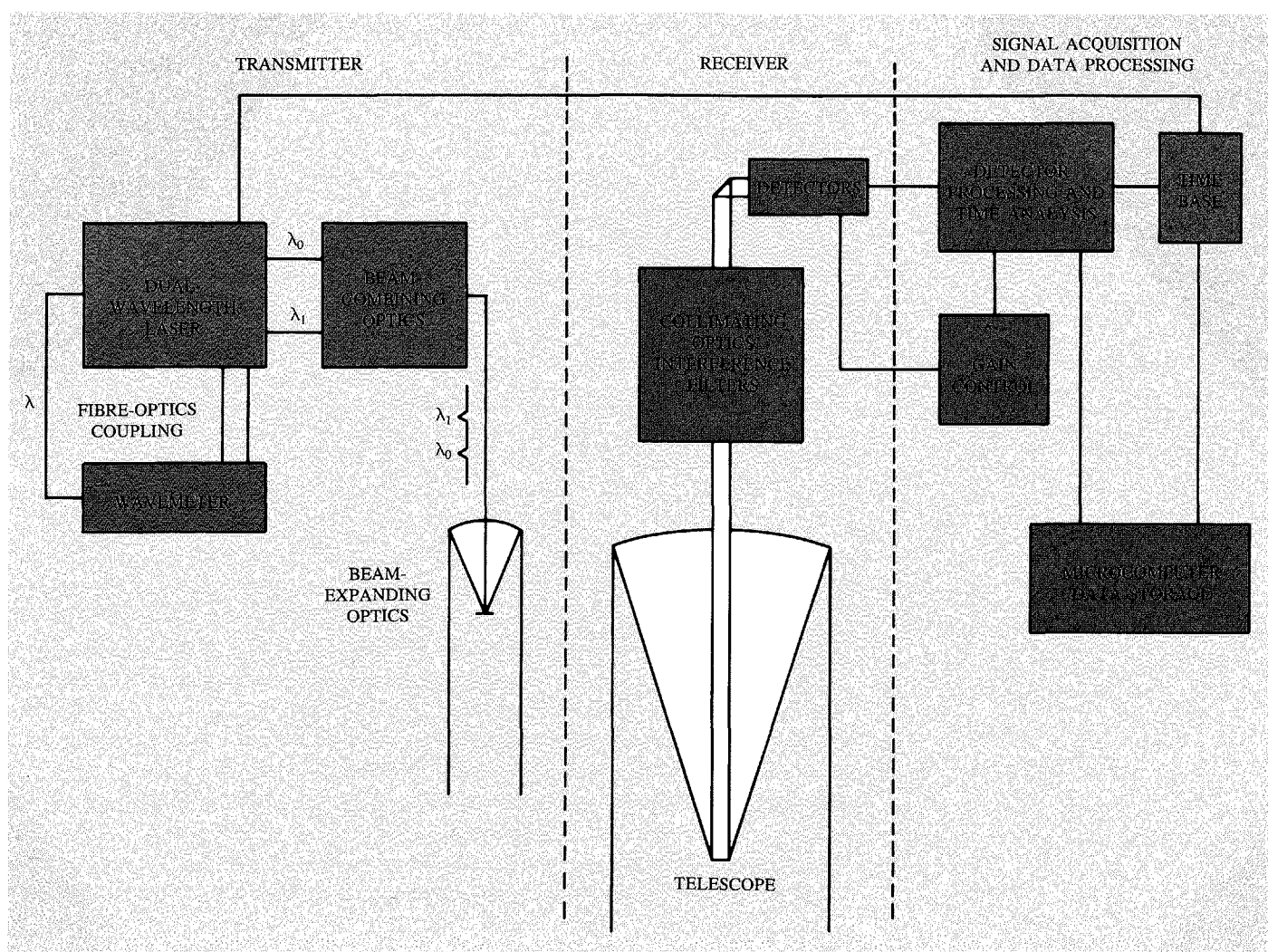
4.6.



Figure 4.5. DIAL lidar developed by CNRS and EDF (France) for water-vapour measurements

Figure 4.6. Tunable dye laser used as transmitter source in the CNRS/EDF DIAL lidar system

Figure 4.7. Mobile DIAL lidar developed by CISE Laboratories (Italy) for pollution monitoring



DIAL measurements of humidity, temperature and pressure are best accomplished in the near-infrared region of the spectrum, where strong, well-resolved absorption lines of water vapour and oxygen exist. In recent years, continued research and development in solid-state laser materials has led to the development of a new class of laser emitting in the appropriate wavelength range. These so-called 'vibronic' lasers are based on ion doping of a dielectric solid matrix. A list of representative tunable vibronic lasers is presented in Table 4.4. Most of these host crystals contain (doping) transition metal ions:  $\text{Cr}^{+3}$ ,  $\text{Ti}^{+3}$ ,  $\text{Ni}^{+2}$ , and  $\text{Co}^{+2}$ .

Cr-ion based lasers have a tuning range of about 100 nm, with a central frequency which depends on the particular host crystal. Alexandrite ( $\text{Cr: Al}_2\text{BeO}_4$ ) is currently the most developed vibronic laser. Allied Corporation in the USA has patented this crystal. In the host crystal of chrysoberyl, the  $\text{Cr}^{+3}$  ion levels are strongly coupled to the lattice giving rise to a very broad fluorescence spectrum from excited electronic states to a manifold of lower vibronic levels, which decay to ground level via phonon emission (vibronic material). The Alexandrite laser has a large tuning range, which extends from about 720 to 790 nm depending on tem-

**Figure 4.8. Schematic of DIAL lidar instrument**

Table 4.4. Selected list of commercial, vibronic and solid-state laser materials

Crystal name	Chemical composition	Application
Erbium-YAG	$\{Y_{3-x}Er_x\}Al_5O_{12}$	Laser at 2.96 $\mu m$ room temp.
Erbium-Chromium YAG	$\{Y_{3-x}Er_x\}[Cr_yAl_{2-y}](Al_3)O_{12}$	Laser at 2.96 $\mu m$ sensitised
Thulium-Holmium YAG	$\{Y_{3-x-y}Tm_xHo_y\}Al_5O_{12}$	Laser at 2.06 $\mu m$
Thulium-Holmium-Chromium YAG	$\{Y_{3-x-y}Tm_xHo_y\}[Cr_2Al_{2-z}](Al_3)O_{12}$	Laser at 2.06 $\mu m$ room temp.
Erbium-Holmium YAG	$\{Y_{3-x-y}Er_xHo_y\}Al_5O_{12}$	Laser at 2.96 $\mu m$
Titanium YAG	$\{Y_3\}[Ti_xAl_{2-x}](Al_3)O_{12}$	Tunable laser 700–1000 $\mu m$
Titanium-Sapphire	$Al_2O_3:Ti^{3+}$	Tunable laser 600–1000 $\mu m$
GSAG:Cr	$\{Gd_3\}[Cr_xSc_{2-x}](Al_3)O_{12}$	Tunable laser 600–700 $\mu m$
GSGG:Cr	$\{Gd_3\}[Cr_xSc_{2-x}](Ga_3)O_{12}$	Tunable laser 600–700 $\mu m$
YSAG:Cr	$\{Y_3\}[Cr_xSc_{2-x}](Al_3)O_{12}$	Tunable laser 600–700 $\mu m$
LLGG:Cr	$\{La_3\}[Cr_xLu_{2-x}](Ga_3)O_{12}$	Tunable laser 700–800 $\mu m$
GSAG:Nd:Cr	$\{Gd_{3-x}Nd_x\}[Cr_xSc_{2-x}](Al_3)O_{12}$	High-power $Nd^{3+}$ 1.06 $\mu m$
GSGG:Nd:Cr	$\{Gd_{3-x}Nd_x\}[Cr_xSc_{2-x}](Ga_3)O_{12}$	High-power $Nd^{3+}$ 1.06 $\mu m$
HLMA:Nd	$LaMgAl_{11}O_{19}:Nd$ (0–15%)	$Nd^{3+}$ laser at 1.06 $\mu m$
HLMA:Nd:Cr	$LaMgAl_{11}O_{19}:Nd:Cr$ (Nd 0–15%, Cr 0–0.5%)	$Nd^{3+}$ laser at 1.06 $\mu m$
Cerium-YAG	$\{Y_{3-x}Ca_x\}Al_5O_{12}$	Scintillation detector, fluorescence converter
SmSGG	$\{Sm_3\}[Sc_2](Ga_3)O_{12}$	Fluorescence converter
YAlO	$YAlO_3:Cr$ or $Ti^{3+}$	Tunable laser potential
GdAlO	$GdAlO_3:Cr$	Tunable laser potential
Titanium-Spinel	$MgAl_2O_4:Ti^{3+}$	Tunable laser potential
Scandium-Borate	$ScBo_3:Ti^{3+}$	Tunable laser potential

perature, pumping power, doping, etc. It features excellent and long-lasting thermal and mechanical properties, similar to Nd-YAG, which permits a very high average power density to be attained without suffering from thermal or optical damage. The present reported average power delivered is 100 W (1 J/pulse, 100 Hz, 0.5% overall efficiency). Commercially available Alexandrite lasers from Allied Chemical are optically pumped with Xenon-filled flash lamps. Efficient pumping is achieved because there is good matching between the high-pressure Xenon emission spectrum and the Alexandrite absorption bands. The laser can reach  $10^7/10^8$  shots, a value set by flash-lamp failure and not by the rod itself, which has the potential of much longer lifetime.

Another important vibronic laser is the Titanium-Sapphire (Ti:  $Al_2O_3$ ), which is tunable over 300 nm around a central wavelength of about 800 nm. This material does not suffer from excited-state absorption, but the short excited-state lifetime makes flash-lamp pumping rather inefficient. Efficient pumping of Ti:Sapphire (40% overall efficiency) has been reported with a frequency doubled Nd-YAG laser pump. Output energies of 100's mJ and very narrow line widths (25 mÅ) have been demonstrated.

The flash-lamp-pumped Alexandrite laser presently looks a strong candidate for DIAL measurements, and an ESA technology development contract is currently examining Alexandrite laser performance requirements for DIAL. However, the attraction of an all-solid-state laser DIAL lidar renders the Ti-Sapphire laser a valid long-term alternative. In this case the Ti-Sapphire would be optically pumped by a second-harmonic Nd-YAG laser; the Nd-YAG laser in turn would be pumped by a suitable laser diode array. The feasibility of the Ti-Sapphire approach relies on the availability of sufficiently high power diode laser arrays, which presently are still not available.

Another basic requirements of DIAL measurements is accurate positioning of the laser emission line with respect to the selected molecular absorption line. Spaceborne DIAL applications require the development of a dedicated subsystem (a wavemeter) to record the emitted laser wavelength, the spectral profile and also provide the required frequency stabilisation. Also, DIAL measurements require two lasers operating at well-defined frequencies, which must be transmitted with very small time separation (the lower limit fixed by time of flight, the upper limit by sampling in the same volume: 300  $\mu\text{s}$  - 1 ms). The requirements on laser emission characteristics are quite different for humidity or for temperature and pressure, and are much more stringent than for backscattering applications (see Table 4.5). In fact the "ON" laser wavelength must be well within the chosen molecular absorption line, i.e. the laser line width must be narrower than the absorption line, and the frequency difference between the two emitted pulses needs to be fixed within a fraction of this line width in order to ensure a satisfactory signal-to-noise ratio. To lock the ON laser frequency to a low-pressure gas absorption line, the line width must be kept within  $0.001\text{ cm}^{-1}$ , and should exhibit a corresponding high degree of frequency stability.

Another aspect specific to DIAL is the Doppler shift that results from beam scanning and spacecraft motion. In fact, for a  $15^\circ$  scan angle, the Doppler shift of the return pulse will increase continuously with each return pulse to about  $0.3\text{ cm}^{-1}$  at the end of the scan, and since this is greater than the emission line width it must be compensated to ensure accurate measurements.

The transmitter-beam expanding telescope and the receiver telescope are the same as for a backscatter lidar, but here additional optics are required to combine or separate the two laser beams to avoid any difference in the scattering volumes. The alignment precision results from a trade-off between the divergence of the laser beams and the receiver field of view, which is based on signal-to-noise and eye-safety considerations. These differ for day-time and night-time measurements, with typical FOVs of 0.1 mrad to 0.5 mrad for day and night time, respectively.

In addition, a dual-channel rather than a single-channel detector assembly is required to handle the two-frequency backscattered signal. The beam scanner is the same, and the data-processing requirements here are about twice those of the backscattering lidar.

Table 4.5. Laser characteristics for DIAL operation

	Water	Pressure, temperature
Wavelength	725–730 nm	760–770 nm
Spectral width	1 pm	0.3 pm
Separation of spectral lines	70 pm	70 pm
Energy per pulse	50–300 mJ	
Stability in output energy	5% ( $1\sigma$ )	
Repetition rate	5–10 Hz	
Temporal pulse separation	100–400 $\mu\text{s}$	
Pulse duration	<300 ns	
Spectral purity	99% of energy in 1 pm	
Absolute precision of centring the wavelengths	0.25 pm ( $\lambda_{\text{on}}$ ), 2 pm ( $\lambda_{\text{off}}$ ), 0.06 pm ( $\lambda_{\text{on}}$ )	
Divergence	< $10^{-4}$ rad	



### 4.3 Doppler Wind Lidar

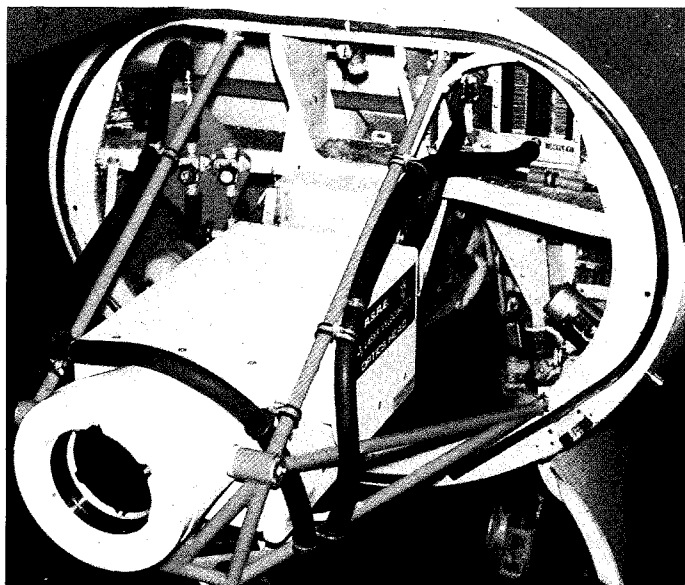
Several ground-based pulsed and CW CO<sub>2</sub> Doppler wind lidars, with short range capabilities (km's), have been developed and employed at various sites in Europe and elsewhere, and autonomous and automated wind lidars have been flown. Among them is the coherent CW CO<sub>2</sub> lidar known as LATAS (Laser True Airspeed System) operated by RSRE and RAE in the UK (Fig. 4.9). This instrument has been flown successfully for over five years and has shown very significant reliability and performance throughout this period. True airspeed, wind shear and turbulence ahead of the aircraft have been measured. Extensive studies of the strength of atmospheric backscatter at 10 micron have been made and a large data base from nearly 90 flights in the Northern Hemisphere, including the Arctic Circle, have now been cumulated. Other European equipment includes the airborne coherent system known as LIMES, from DFVLR in West Germany. This ground sensing equipment operates with four CO<sub>2</sub> lasers tuned to different wavelengths in the 9 – 11 micron band and is employed in the classification of rock and soil types. In France a CW CO<sub>2</sub> coherent system has been built by Crouzet SA and flown very successfully in a helicopter. The equipment incorporates conical scanning for ground-speed as well as air-speed measurement. A more compact system has recently been installed in an aircraft. Development of a pulsed coherent CO<sub>2</sub> lidar system for both airborne and ground based applications is under way at the Laboratoire de Meteorologie Dynamique (CNRS-CNES).

Figure 4.9. Laser True Airspeed System (LATAS) developed by RSRE/RAE (UK)

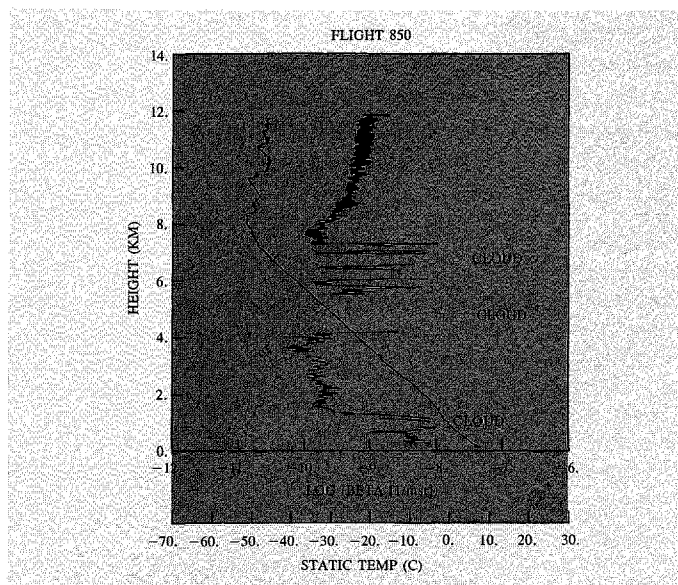
Figure 4.10. Backscattering lidar profile at 10 micron obtained with the LATAS system during aircraft climb. Log records cloud at <1 km and in and out of cloud at 4–7 km, with clear air above. Note the steady increase in b(p) as the aircraft climbs above the low tropopause and into the stratosphere from 8 km

In the United States a ground-based pulsed wind Doppler lidar operating at 2 J/pulse, 50 pulse/s has been developed at the NOAA WPL laboratory and is used mainly for the observation of local atmospheric transients such as gust fronts and outbursts (Fig. 4.11). NASA/Marshall Spaceflight Center has flown a CO<sub>2</sub> Doppler lidar (10 mJ/pulse at 110 pulse/s) aboard an Ames Convair 990 aircraft for wind-field and backscattering-coefficient measurements.

The Doppler wind lidar instrument includes the same basic subsystems as other lidar instruments (Fig. 4.13). In the Doppler lidar, however, in order to be able to measure wind with a relative accuracy of 1-2 m/s in the lower troposphere, stable single-mode laser emission must be achieved and maintained during the laser time of flight. In addition, since only aerosol backscattering is of interest here and the



4.9.



4.10.



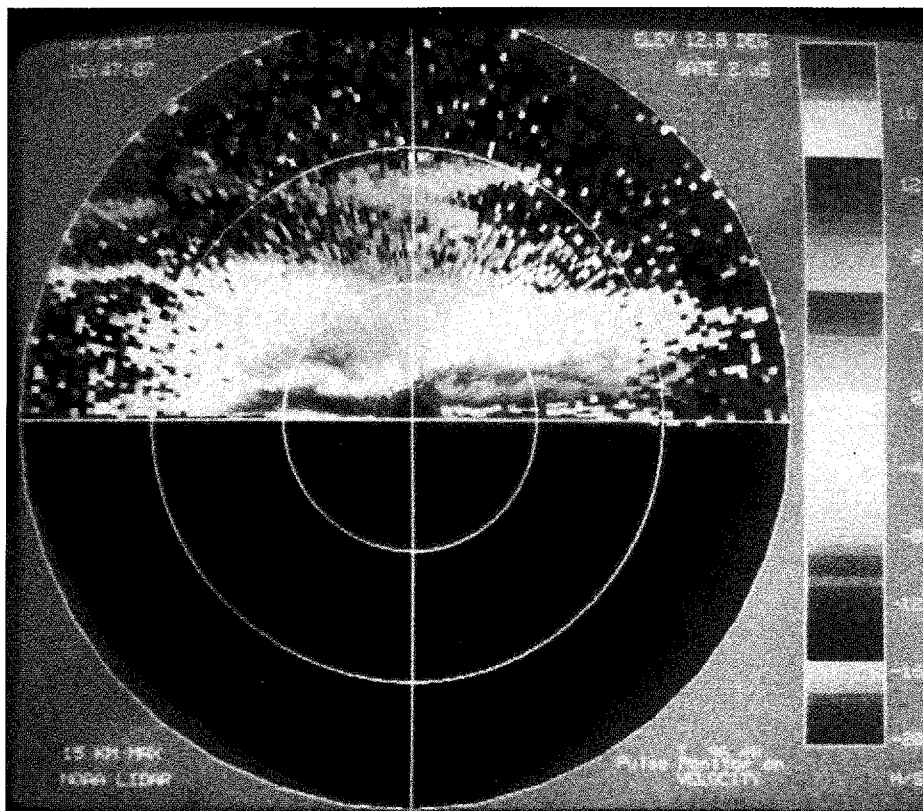


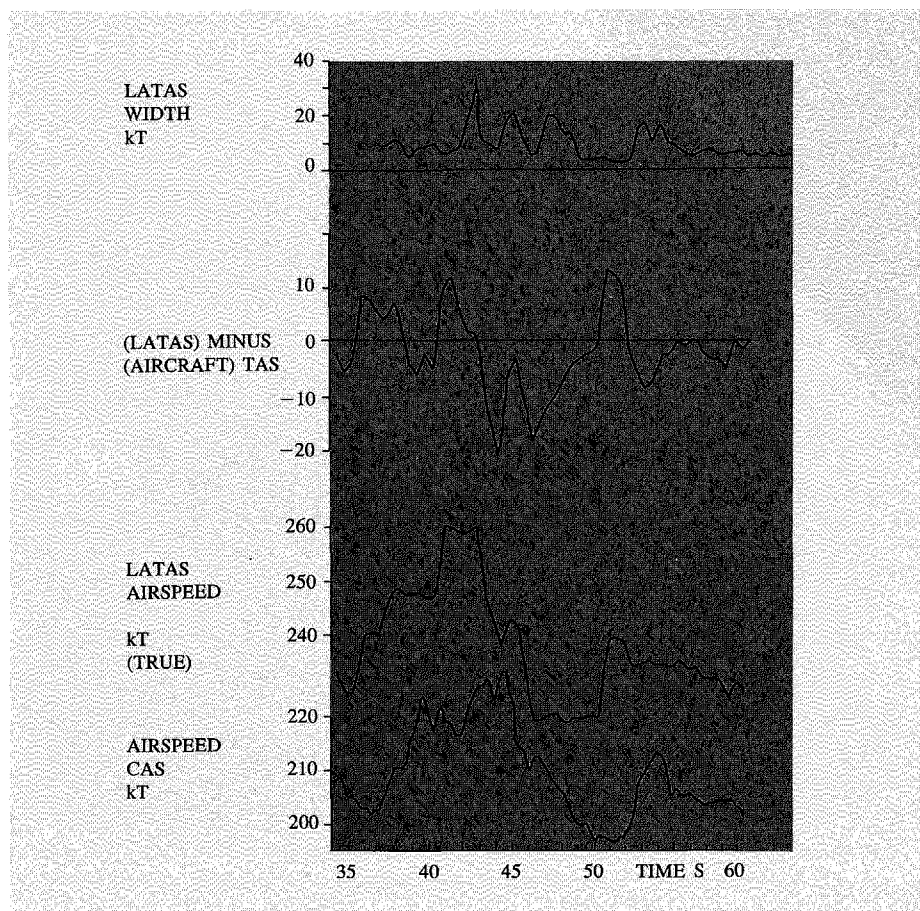
Figure 4.11. Atmospheric turbulence observed with the NOAA pulsed Doppler lidar. The display shows the wind fields associated with the passage of the dry line, i.e. the sharp boundary between moist and dry air in the south central USA. Radial velocity is indicated by colour; range rings are at 5 km intervals. The moist air has moved from the right of the picture and has passed the lidar. Velocities at lower levels show winds blowing towards the moist-air/dry-air interface at speeds of up to 15 m/s. (Courtesy R.M. Hardesty, NOAA Wave Propagation Laboratory, USA)

accuracy requirements are tight, the pulsed laser energy required is about a factor of 10 higher than that required for backscattering applications.

Four different systems have been proposed based on both coherent and incoherent detection with laser emission at either 10  $\mu\text{m}$ , 1  $\mu\text{m}$  and 0.5  $\mu\text{m}$ . Thus, the most suitable candidates for spaceborne applications are the  $\text{CO}_2$  laser and the Nd-YAG laser. The  $\text{CO}_2$  laser with coherent detection appears to be the preferred choice in the near term, thanks to its long-standing heritage; while the Nd-YAG laser or solid-state laser routes, with direct detection, appear candidates more for the longer term. The main features of the Nd-YAG laser have been already presented for the backscattering lidar case: the major problem areas, in addition to lifetime, are the two contrasting requirements of eye safety and energy level.

The  $\text{CO}_2$  laser, together with Nd-YAG laser, is the most advanced and widely used laser in both research and industrial applications. The  $\text{CO}_2$  laser is a gas laser that can be excited efficiently in an electric discharge to some vibrational rotational states radiatively coupled to a manifold of lower vibrational states. The  $\text{CO}_2$  laser can be tuned over a number of lines covering the wavelength range 9-11 microns; the tuning capability depends on the operating pressure: at 1 atm of gas, the laser can operate on discrete lines with a gap of about 50 GHz. Since an electric discharge is generally used to pump the laser, rather high voltages are required (typically 15 kV/cm at 1 atm gas pressure), and this can present a problem for spaceborne applications. The  $\text{CO}_2$  laser can operate from subatmospheric pressures to several atmospheres, but trade-offs between energy extraction, system complexity and voltage requirements limit the domain of operation to about 1 atm

Figure 4.12. Wind measurements with the LATAS instrument. The figure records the passage through a thunderstorm microburst

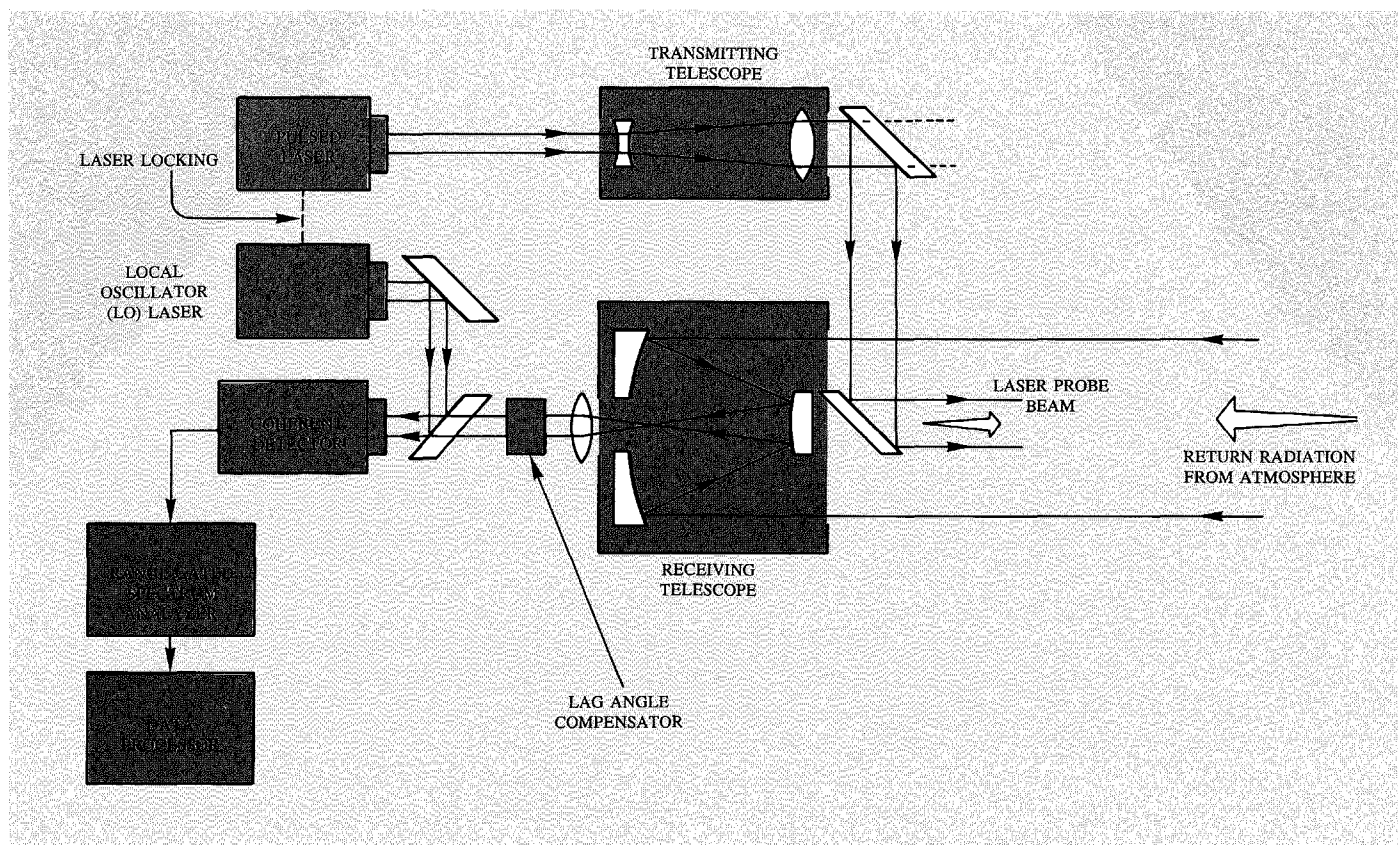


for spaceborne applications. The CO<sub>2</sub> laser is very efficient. It has a wall-plug efficiency of about 10%, it can operate in a continuous-wave, Q-switched or mode-locked mode, and subnanosecond pulses can be generated in a high-pressure discharge.

As far as the lifetime problem is concerned, which for the CO<sub>2</sub> laser originates from contamination and dissociation, recent progress in catalysts indicates that lifetimes of more than  $10^8$  pulses can be achieved in the near future.

For wind-vector determination and global coverage, it is necessary to scan the laser beam across the ground track with a rather large nadir angle. Conical scanning has been found suitable for wind vector determination. As already pointed out during the discussion on the backscattering lidar, during scanning a lag angle is produced between the receiver FOV, and the direction of the backscattered beam due to the combined effects of the scanner rotation and spacecraft's translational motion. Since this angle is larger than the receiver FOV, and, in addition, changes during the arrival time of photons, it must be very precisely compensated, within a fraction of the transmitted beam divergence, to maintain good receiver efficiency.

The wind-detection system is rather complex compared to the backscattering lidar, since the wind detection involves measurement of a phase difference between the transmitted and received pulses, rather than the measurement of a signal intensity. As previously mentioned, two different detection systems can be



**Figure 4.13. Schematic of a coherent Doppler wind-lidar instrument**

used which have different detection sensitivities and technological complexities: coherent detection with a suitable heterodyne receiver, or direct detection with a multiple Fabry-Perot interferometer.

In the coherent Doppler lidar at 10 micron with a CO<sub>2</sub> laser source, the spectral analysis of the heterodyne signal can be accomplished with a bank of SAW (Surface Acoustic Wave) filters or by employing correlation-type analysis. The raw data are generated at about 1 – 2 Mbit/s, which is about a factor of 10 higher than for backscattering lidar. On-board processing would, however, reduce the required data transfer to ground. The high accuracy required for pointing and lag-angle correction imposes additional on-board instrumentation such as star trackers, or gyros, as for the altimeter case, and scanners with accurate lag-angle compensation capability.

Coherent Doppler lidar at 1 micron with the Nd-YAG laser and heterodyne detection seems to be ruled out, in view of the severe pointing-accuracy and the eye-safety requirements, which appear very difficult to meet.

With the incoherent wind Doppler lidar, at doubled Nd-YAG frequency or in an eye-safe spectral region (i.e. above 1.5 microns), the pointing stability, and lag-angle correction are less severe. The energy specifications of the transmitter laser, now very demanding, could be reduced to realistic values if the receiver efficiency can be improved. Excimer lasers are not considered strong candidates due to the very high voltages required (30 kV). Spectral analysis for the incoherent Doppler wind lidar is quite complex and requires suitable multiple Fabry-Perot interferometers and associated array detectors.

#### 4.4 Altimeter-Ranging

The laser altimeter-ranging instrument can provide accurate point positioning or distance measurement from space to some specified location on Earth by means of time-of-flight measurement.

Various ground-based laser ranging instruments (SLR, see Table 4.6 for Europe) are currently in operation, ranging with centimetre accuracy to the two satellites LAGEOS and STARLETTE in the context of crustal-dynamics studies.

Two basic types of spaceborne laser ranging instruments can be identified: laser ranging to retroreflectors, mainly for geodynamics purposes, and laser altimetry, which addresses primarily ice dynamics and topographic mapping of land and ice.

In the lidar altimeter, a laser pulse is reflected off a diffuse scattering surface such as a polar ice cap, water surface, or inland terrain or vegetation, and the distance from the satellite is inferred by the time of flight of the laser pulse. Generally, the ranging accuracy required is in the range of decimetres.

For altimetry applications there are special requirements on beam scanning, or pointing and tracking. The required decimetre distance accuracy of decimeters does not pose severe technological problems on host spacecraft or laser performance.

In the retroranging lidar, a nanosecond laser pulse or a two-colour picosecond laser pulse is reflected off an array of passive retroreflectors (mirrors) located in some region of tectonic interest (such as along a fault zone), and the relative distance change between these reflectors is measured, again with the laser time of flight.

For ultra-precise point positioning in laser ranging, the system requirements and feasibility concept were assessed in the ESA SPALT study (1980), where a representative mission model was studied and the instrument performance characteristics identified. The needs of a dual-wavelength picosecond ranging system for sub-centimetre accuracy were identified, and ESA subsequently initiated preliminary technology developments in picosecond laser sources and picosecond streak camera detectors. For centimetre-precision ranging, and particularly for sub-centimetre ranging, there are severe requirements on laser performance, on beam pointing and tracking precision, and on spacecraft orbit and attitude knowledge, with sub-microradian beam-pointing resolution requirements.

Model calculations show that centimetre-accuracy ranging could be obtained with a single-colour nanosecond laser system and state-of-the-art pointing systems, but an atmospheric sounder would be needed on board to provide the atmos-

Table 4.6. Main characteristics of laser ranging stations in Europe, March 1984

	Dionysos	Grasse	Graz	Herstmonceux	Kootwijk	Metsähovi	San Fernando	Wettzell
Wavelength (nm)	694	694	532	532	694	694	694	532
Max. energy (J)	0.75	4	0.1	0.03	3	1	1	0.25
Pulse width (ns)	5	2	0.1	0.15	2	25	12	0.2
Repetition rate (ppm)	60	15	600	600	15	4	60	240
Minimum beam divergence (arc.sec)	80	5	20	20	60	200	60	5
Receiver aperture (cm)	45	100	50	50	50	63	36	60
Single-shot rms (cm)	20	20	5	5	20	100	75	5
Daylight capability	yes	yes		yes	yes	no	no	yes
Lageos daylight capability				yes				yes

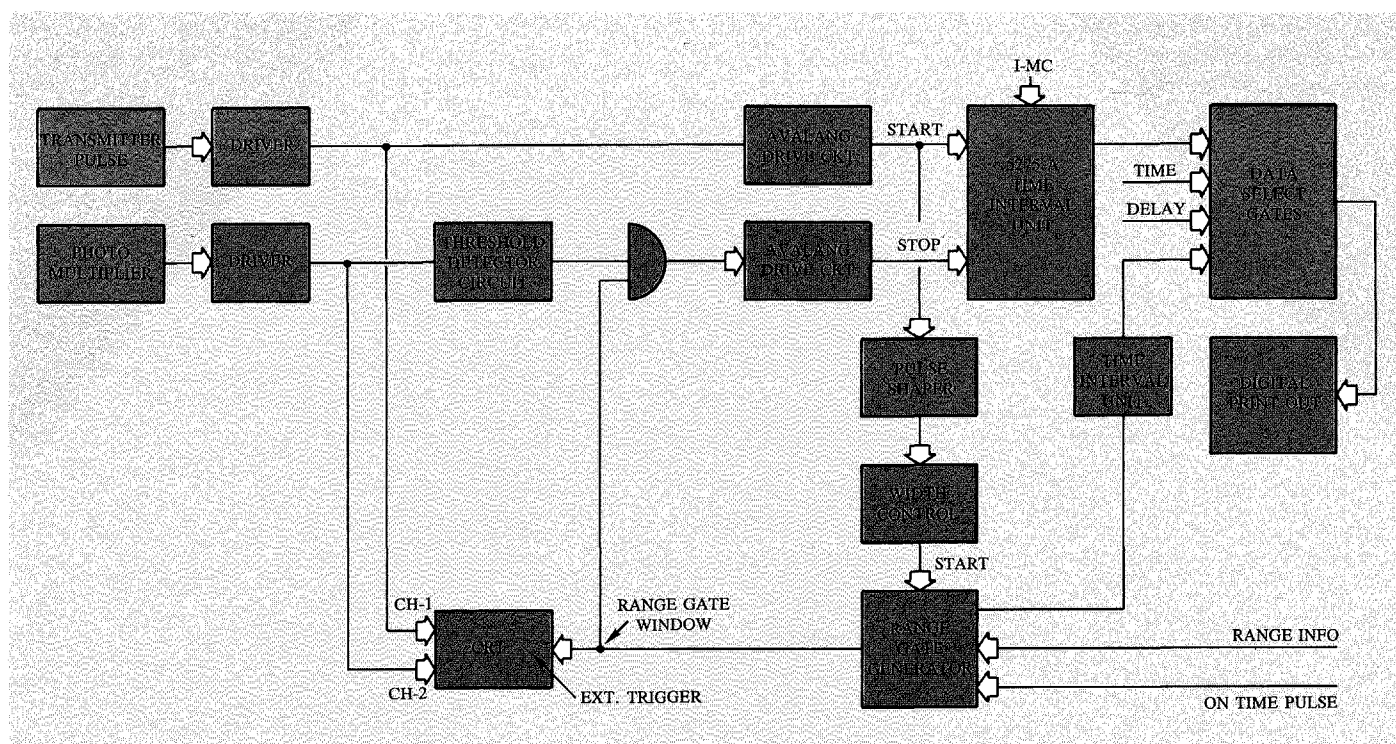


Figure 4.14. Schematic of an altimeter/ranging lidar

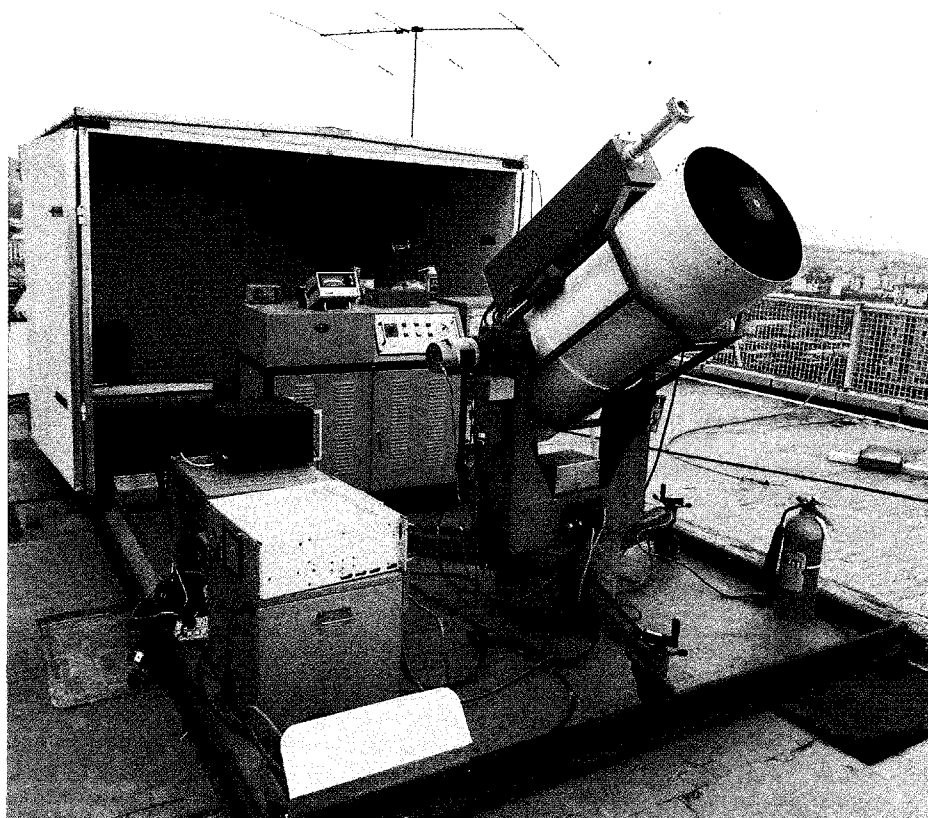
pheric correction. However, size and power requirements might be a problem for space applications (few cubic metres, and power of few kW's required for a one-colour nanosecond laser ranging instrument). For a sub-centimetre laser ranging system, achieving the necessary accuracy from space appears a problem, as precision will ultimately be limited by gravity effects in the low orbits considered for such a mission.

The laser altimeter can be considered as an extension of the backscattering lidar. It consists of the same basic components as other lidar instruments, i.e. transmitter, receiver, signal processor and data-transmission unit. However, since essentially time-of-flight measurements are performed, additional components are required:

- A timing and counter unit, which includes a quartz or caesium clock, and a standard counter. This unit sets the reference time on board and counts the elapsed time from sending to receiving the light pulse.
- Attitude and position measuring instrumentation. This includes an inertial reference unit and one or more star trackers for attitude measurement, as well as a range and range-rate instrument for satellite-orbit determination. The attitude knowledge is important for knowing the instrument pointing angle: a precision of roughly 10 arcsec is required for an altimetry error of about 10 – 20 cm. Also, knowledge of the orbit is required with a precision of around 10 cm. The PRARE instrument, for example, which will be flown on ERS-1, can provide this range precision.

The onboard computer provides for navigation and attitude control of the spacecraft. It can give an a priori calculation of the distance, set the range window,

**Figure 4.15. Laboratory model of an altimeter/ranging lidar developed by the IROE laboratory of CNR (Italy)**



provide for pointing adjustment and determine all the necessary system operating conditions.

For the transmitter laser, the same system options as those for the backscattering lidar apply, i.e. either a Nd-YAG or a vibronic laser appears to be the best candidate for both altimetry and ranging applications. The lifetime issue need to be assessed against the type of applications, since the temporal-coverage requirements varies according to the mission objectives.



# Chapter 5

## Key Technology Areas for Spaceborne Lidar

The potential applications for spaceborne lidar have been identified in the previous chapters in terms of both scientific objectives and technology requirements. They include:

- backscatter lidar for cloud and aerosol measurements
- DIAL lidar for measurements of meteorological parameters (pressure, temperature, water vapour)
- Doppler wind lidar
- Laser altimeter and ranging.

which have now received the support of large user communities. The four laser sensors mentioned above have in fact been proposed by various remote-sensing working groups during the last two years (POPE, COPE, France-UK working group, etc.) as candidate instruments for future Earth-observation space missions. Obviously, these choices take into account the future increase in the availability of large space platforms which could accommodate active sensors during the coming decade (e.g. Polar or Co-orbiting Platforms, EURECA, etc.). It therefore seems appropriate to fix the timeframe for the development of an operational spaceborne lidar, making it compatible with a first flight in 1997, the probable launch date for the European Polar Platform. This does not preclude the exploitation of earlier flight opportunities for short-duration missions (Spacelab-type flights), as they will not require the same level of development and system complexity.

Taking into account the time required for space component qualification and integration onboard a multi-instrument platform, research and development work should be undertaken immediately on the various lidar systems considered above.

The purpose of this chapter is to identify the key components for technology development and provide guidelines for a coherent research and development plan for the next five to eight years (1988-1995).

### (a) Laser considerations

The main laser candidates (Table 5.1) for backscattering applications have been identified as the solid-state Nd-YAG (and Glass) and vibronic lasers, in particular Alexandrite. A backscattering lidar operating at 10 micron, with the CO<sub>2</sub> laser,

### 5.1 Backscatter Lidar

Table 5.1. Main laser candidates for backscattering lidar

	Nd-YAG	Nd-Glass	Alexandrite	Ti-Sapphire	CO <sub>2</sub>
Wavelength (nm)	1064	1040	720—780	710—950	9000—10000
Power, average (W)	> 100	> 100	≤ 100	≪ 100	> 100
Nature of output	CW & pulsed	CW & pulsed	CW & pulsed	CW & pulsed	CW & pulsed
Lasing medium	Crystal	Crystal	Crystal	Crystal	Gaseous
Efficiency	1% [8%]*	1—3%	≤ 1%	1—2%**	8%
Lifetime limit	Flash lamp	Flash lamp	Flash lamp	Flash lamp	Gas chemistry
Type of pump	Flash lamp	Flash lamp	Flash lamp	Visible laser	Discharge
Tunability	Laser diode ≤ 5 cm <sup>-1</sup>	≤ 150 cm <sup>-1</sup>	720—780	710—950	Lines from 9000 to 10000

\* With diode laser pumping

\*\* With a frequency-doubled diode-laser pumped Nd-YAG laser as pump source

would also be of interest especially if a CO<sub>2</sub>-laser-based lidar instrument is developed. In choosing the most appropriate laser for backscattering applications, one should consider:

- maturity of technology
- availability of the various components
- compliance with spaceborne requirements, especially lifetime.

On these bases, the Nd-YAG laser appears to be the best candidate for early space implementation. It benefits from better thermal and mechanical characteristics for laser emission than the Nd-Glass laser or vibronic crystal laser, thereby allowing a higher efficiency and repetition rate. Taking into account the rapid decrease in atmospheric scattering efficiency with increasing wavelength, it will allow all the measurement capabilities of a backscatter lidar (as reviewed in Chapter 3) to be exploited, without added complexity in the detection scheme (direct detection), whereas a CO<sub>2</sub> laser source will certainly require a coherent detection scheme to achieve the same results. The Nd-YAG laser can also be very efficiently pumped with laser diodes, thereby opening up the route for an all-solid-state laser. Furthermore, Nd-YAG laser sources can also be considered as potential sources for other systems as the DIAL lidar (pumping a Ti-Sapphire crystal), wind Doppler lidar (coherent and incoherent system at 1 micron and 0.5 micron) or laser-ranger and altimeter applications.

The most critical area is the laser lifetime; for a system operating at a repetition rate of 10 Hz, a three-year mission duration would require laser component lifetimes of approximately  $10^9$  pulses. For these lifetimes the most critical component is presently the pumping device, although other components, such as optical and electronic components, can also be considered as critical.

For the Nd-YAG laser, two optical-pumping techniques are considered: flash-lamp pumping and the more recent technique of laser-diode pumping. Flash lamps have been employed successfully so far to pump near-infrared or visible lasers with efficiencies up to about 2%. Flash lamps exhibit rather high power capabilities. For the typical operating conditions of interest here, lifetimes can reach approximately  $10^7$  to  $10^8$  shots.

Laser diode pumping of Nd-YAG has undergone a very rapid growth over the past few years but present applications are limited to low-power devices. InGaAsP/InP laser diodes, produced in Europe with ESA support and suitable for laser communication at 1.5 micron, have been manufactured at STC in England. They have emitted power densities of  $6.8 \text{ MW/cm}^2$  for over 6000 h. Diode arrays manufactured by Siemens in Germany for optical pumping can produce multi-mode pumping powers of approximately 15 W. Recent development work at McDonnell Douglas in the USA has shown that a continuous-wave pumping power of 15 W can be achieved, resulting in a Nd-YAG output power of 1.8 W. Now diode arrays from Spectra Diode in the USA with 10 W peak powers at 100 pps are becoming commercially available.

#### **(b) Transmitter and receiver optics**

The key optical element of the transmitter is the beam scanner, with its associated beam lag angle compensator. As noted in Chapter 3 for backscattering applications, with a typical receiver telescope FOV of 0.1 mrad, only the constant large



lag angle needs to be compensated; the other two contributions are too small to be of practical importance.

The beam scanning leads to some problem areas that need to be addressed, in particular: What type of scan (linear or conical?), or what scan angle and scan period can be allowed? Large scan angles increase the coverage area on ground, but at the expense of increased technological difficulties and reduced height accuracy. The spacing of points on Earth also depends on the scanner design, which must therefore be properly considered. The scanner movement can affect the attitude of the host spacecraft, especially if a high-mass mirror is involved, and this aspect must therefore be considered. In addition, the type of scanning affects the lidar data acquisition and evaluation processes.

The key optical element of the receiver is the light-collecting telescope. Large telescope mirrors can increase the signal-to-noise ratio, but do pose more technological problems (mass, optical quality, scanning angle, etc.) than smaller ones. For backscattering lidar applications with direct detection, however, the telescope does not need to operate in diffraction-limited mode, and therefore it is not difficult to fabricate a relatively large mirror (say 1 m diameter) with the required optical quality. Another critical aspect to consider, especially for a polar-orbiting space mission, is the combined effect of hard radiation and high pulsed energy.

#### **(a) Laser considerations**

The main laser candidates for DIAL operations are two vibronic lasers, namely Alexandrite and Ti-Sapphire, which can be tuned over selected absorption bands of molecular oxygen and water (720, 770 nm). Due to its short upper-state lifetime, Ti-Sapphire cannot be pumped as efficiently with flash lamps as Alexandrite. Faster pumping rates are therefore required, and these can be achieved with the help of a high-power visible laser. In the short term, Alexandrite is the best laser candidate. It is foreseen, however, that an all-solid-state approach, based on a diode-pumped Nd-YAG laser which, in turn, pumps a Ti-Sapphire or equivalent vibronic laser, could fulfil the reliability and lifetime requirements posed by a multi-year duration mission, in the longer term.

The laser performance requirements for DIAL operation are rather critical, in particular the narrow line width required for pressure and temperature measurements, and the necessary frequency stability of the "on resonance" emission.

#### **(b) Transmitter and receiver optics**

The considerations for backscattering lidar are also valid for the DIAL case. For the transmitter, since two laser beams are involved, it is important that a suitable low loss combination of beams can be generated without optical damage problems. In addition, a critical aspect is the frequency control of the "on-resonance" beam. Appropriate wavemeters are being developed: they use a combination of different etalon plates and/or wedges to determine the frequency of the laser pulse with reference to a frequency standard. An alternative technique could be to use an opto-acoustic cell filled with some reference absorbing gas at low pressure.

Another critical area that must be properly addressed is associated with the dynamic Doppler shift that affects the received beam as a result of spacecraft motion and beam scanning.

## **5.2 DIAL Lidar**

### 5.3 Doppler Wind Lidar

As seen in Chapter 4, four techniques have been proposed for global wind measurement: two coherent techniques (at 10 and at 1 micron) and two incoherent techniques (at 0.5 and at 0.3 micron).

#### (a) Coherent Doppler lidar considerations

With Nd-YAG lasers operating at 1 micron, the eye-safety requirements are severe for the pulse energy and beam collimation needed. In addition, very high pointing accuracy and lag-angle correction (sub microradians) are required.

Coherent wind measurement at 10 micron with a CO<sub>2</sub> laser is currently considered the most viable solution for space use. No eye-safety problems are foreseen at this wavelength, and the pointing requirements are less severe at 10 micron (with a 1 m telescope, several microradians pointing error short term and 100's microradians long term appear adequate).

The critical technology area at 10 micron is probably the pulsed CO<sub>2</sub> laser transmitter. The technical specifications in terms of pulse energy, pulse length, and laser frequency stability, line width and lifetime therefore require careful definition, and obviously depend on the parameters of the space platform and the task in hand. They are likely to prove demanding, but recent progress in CO<sub>2</sub> pulsed laser technology has generated confidence that advanced specifications can be met provided development funding is initiated in the near future.

Other key components that need further R & D effort are:

- Detectors; high-sensitivity (quantum efficiency 40%), high-bandwidth (up to 2 GHz) detectors are available from a number of European suppliers. Rapid progress is also being made in the development of reliable closed-cycle refrigerators for detector cooling.
- Signal processors; several possible signal-processing methods are available and include spectral analysis with, for example, fast digital Fourier-Transform or banks of Surface-Acoustic-Wave (SAW) filters, or correlation-type analysis.

#### (b) Incoherent Doppler lidar considerations

Two different laser technologies can be considered today.

##### (i) Nd-YAG lasers, frequency-doubled to 530 nm, or frequency-tripled to 350 nm.

The major advantage of the incoherent technology, compared with the coherent method lies in the relaxation of the requirements for accurate pointing, matching and co-alignment of transmitter/receiver beams. The receiver telescope no longer needs to be diffraction limited. The Doppler analysis is performed with a relatively simple interferometer, of a type which has already been fully space qualified, namely a Fabry-Perot interferometer, with a fast, multichannel photon counting detector.

Considerable care has to be taken with the overall optical design of the system to maximise telescope and optics transmission efficiency, and similarly in the optimisation in the efficiency of the detector package. A trade-off between maximum achievable energy and receiver efficiency needs to be made. In fact, optical losses in the frequency doubling or tripling must be minimised, and the transmission of the complete receiver and quantum efficiency of the detector have to be maximised. At 530 nm, care has to be taken to ensure that the transmitted beam meets ground-level eye-safety requirements, but this is feasible. At 350 nm, the eye-safety problem is greatly relaxed, but the inherent additional loss of power in frequency-

tripling implies larger input power and total energy demands for the same performance as an overall wind-measuring system.

*(ii) Excimer lasers, operating at 350 nm*

The excimer laser technology is relatively well advanced, and can meet performance and efficiency requirements. It is relatively eye-safe. The present major limitation for space application is the relatively large physical size, and a very significant high-voltage requirement. This would be a major development problem.

Critical areas for development are:

- laser performance and efficiency
- frequency doubling / tripling efficiency
- high-resolution Fabry-Perot interferometers
- fast multi-channel photon counting detectors, and associated high-performance electronics / data processing
- precision wavemeters.

For altimetry or centimetre precision ranging, Nd-YAG laser technology can already provide the performance characteristics needed. Lifetime is a less critical issue because the laser is operative for only short periods of time, although at high repetition rate (20-50 Hz or more, in burst mode desirable for ranging).

Critical areas for altimetry are the requirements on knowledge of the beam pointing angle with respect to nadir to minimise the altitude error, and the knowledge of spacecraft position to locate the beam's ground footprint during the altimetric or mapping measurement. Present star-tracker technology can provide pointing-angle knowledge better than the 10 arcsec required. Hence range and range-rate microwave instruments such as PRARE or DORIS can provide the requisite orbit knowledge with decimetre precision.

The transmitter and receiver subsystems (detection and signal processing) are very similar to those employed in ground SLR systems.

The criticality of the size and power requirements for altimetry/ranging need to be assessed.

For subcentimetre laser ranging systems, three very critical areas are: the dual-wavelength picosecond laser, the sub-arcsecond pointing precision, and the picosecond acquisition and detection system required.

## 5.4 Altimeter-Ranging



# Chapter 6

## Conclusions

Given today's technology and level of understanding, the successful deployment of a lidar instrument in space requires that appropriate studies/development efforts be undertaken in several different areas. The Working Group's recommendations in this respect involve two different types of action:

- technology developments in already identified critical areas, which have to be undertaken immediately;
- system or subsystem studies, including possible scientific studies, that will provide a better assessment of future technology development efforts, to be undertaken in a one to three year time frame.

The Space Laser Working Group envisages a technology-development programme for backscatter, DIAL, wind lidar and laser-altimeter instruments which takes into account on the one hand the impact of these sensors on the scientific and user communities and relevant technology issues, and on the other, the expected mission-opportunity scenario in Europe, including ESA's In-Orbit Technology Demonstration Programme (TDP) and the Polar (or Co-orbiting) Platform of the International Columbus Space-Station Programme.

Figure 6.1 shows the recommended implementation scenario based on the likely future evolution in Europe's space programmes over the next 15 years. In view of the increased payload capability that will become available with the next generation of platforms, particularly the Polar and Co-orbiting Platforms, it seems appropriate to assume that the first flight of an operational lidar instrument could take place in 1997 (scheduled launch date for the European Polar Platform). Earlier flight opportunities are considered feasible for short-duration demonstration missions requiring lower system-reliability levels and lifetimes.

The backscatter lidar is seen as the most promising and realistic lidar candidate for early deployment in space. The DIAL and wind lidars are proposed for later deployment, for reasons of system complexity and degree of development needed, i.e. for 1998 and beyond.

In view of the time needed for space component qualification and integration onboard a multi-instrument platform, research and development work needs to be undertaken immediately on the various lidar systems.

To allow the deployment of a backscatter lidar at IOC (Initial Operational Capability), it will be necessary to solve the basic technology problems by 1991, so that Phase-C/D instrument development can start on time. The main technology issues to be resolved are those related to component lifetime and reliability, considering the three-year minimum operating time for meteorology applications. It is suggested that a conventional Nd-Yag laser be used as transmitter source, and that work be started immediately to achieve the necessary lifetimes for flashlamps and optical components.

As a matter of urgency, a scientific study is needed to assess quantitatively how lidar measurements of scattering and extinction properties of the atmosphere, i.e. cloud top heights, cirrus cloud and boundary-layer height, can be used to improve passive sensor retrievals of meteorological parameters such as temperature, moisture and wind. Such a study will serve as an input (of particular importance for sampling and horizontal resolution problems) for a global system study to be performed in a follow-on phase.

In parallel with these developments, but not necessarily for mandatory application in the first-generation instrument, the problems of diode pumping and use of slab geometries need to be investigated. If successful, they could be employed for

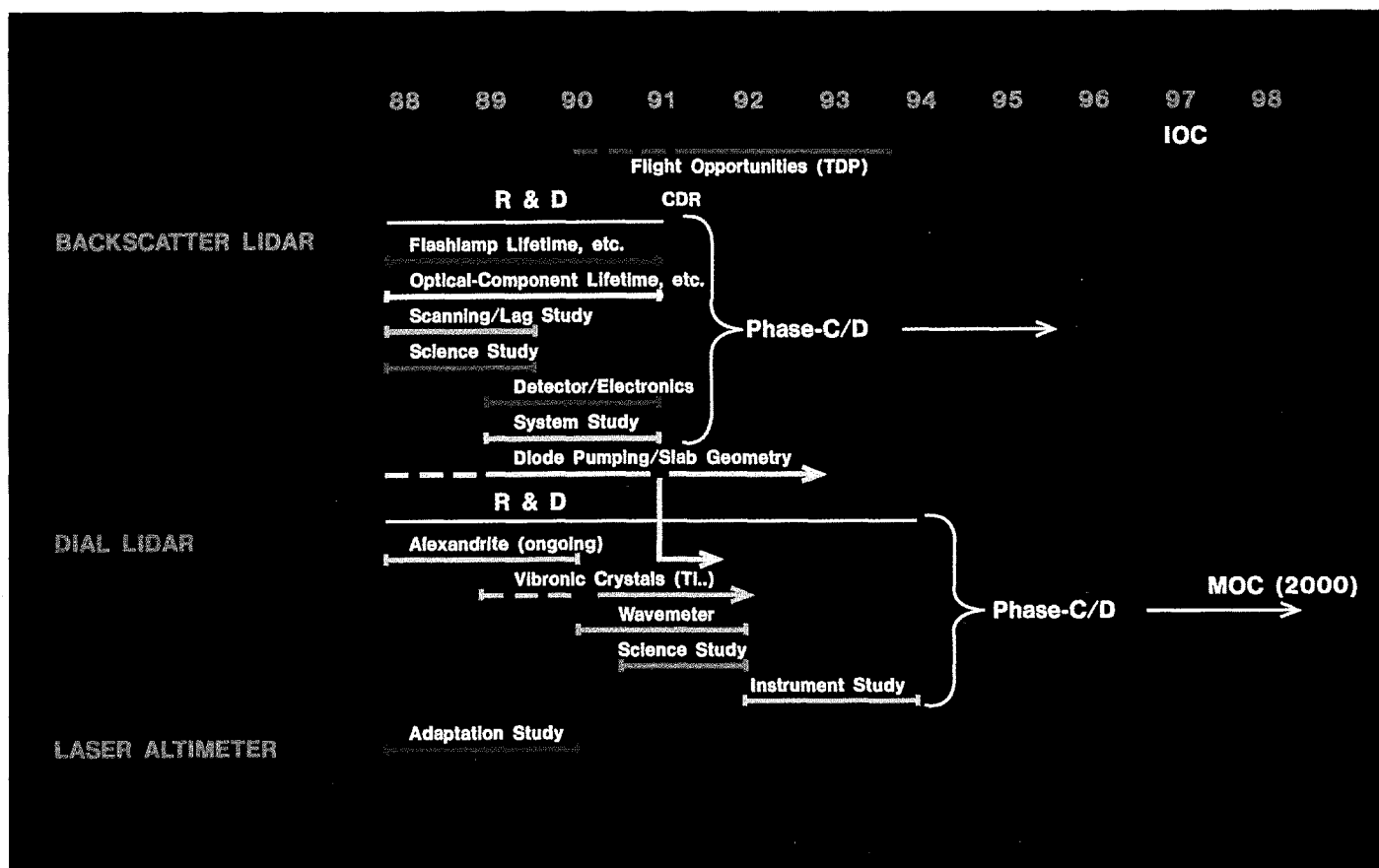
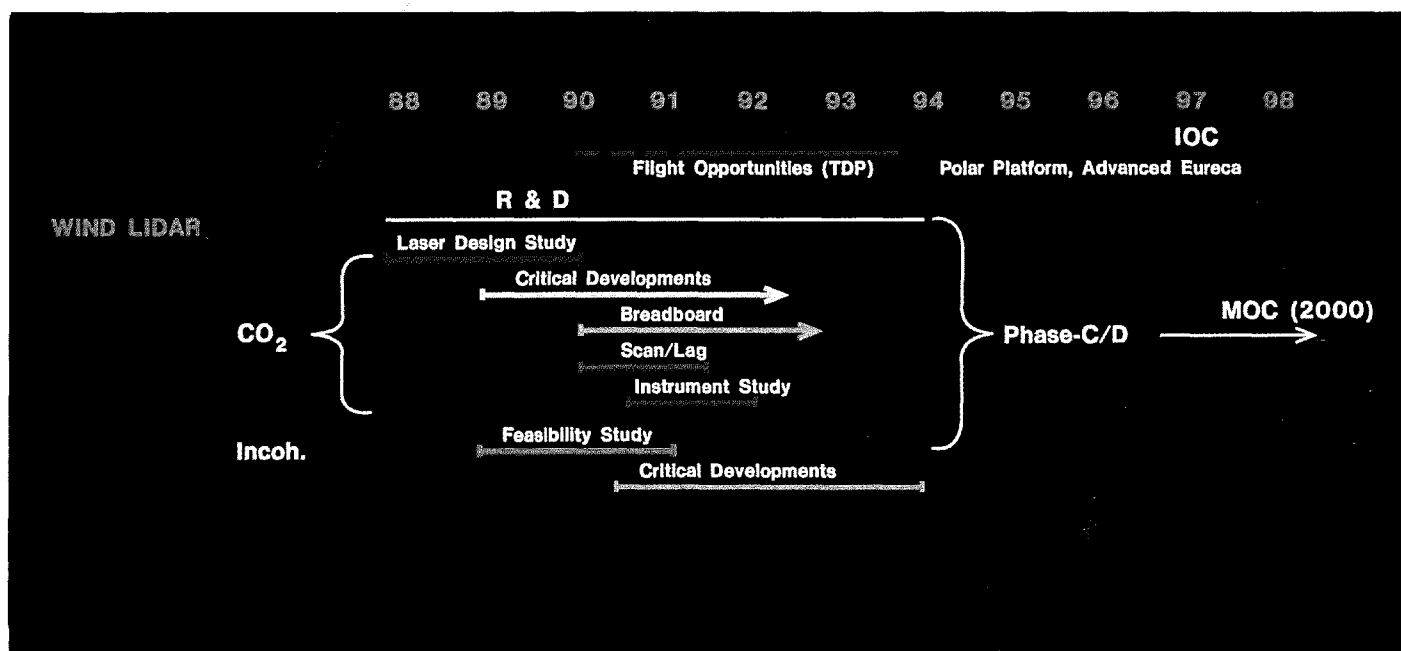


Figure 6.1. Implementation scenario for spaceborne lidar systems.

(a) Backscattering lidar, DIAL lidar and laser altimeter

(b) Wind lidar



the first candidate backscatter lidar, or for the DIAL lidar foreseen for later deployment.

The DIAL lidar is considered to be a follow-on system building on the Nd-Yag technology developed for the backscatter lidar. The suggested baseline approach is to use a basic Nd-Yag source in conjunction with Ti-Sapphire vibronic crystals to produce the lambda-on and lambda-off pulses. Alternatively, the capability of an Alexandrite laser to produce the desired pulse pair should be explored based on the basic technological work already carried out by ESA. Attention should also be paid to realizing adequate wavelength control techniques. Current wavemeter technology is considered adequate, but operation in the space environment needs to be confirmed. A critical point in DIAL measurements from space will be the achievement of sufficient signal-to-noise ratio, and detailed scientific and instrument-definition studies are suggested.

For global wind measurements, the preferred candidate technology is the CO<sub>2</sub> coherent Doppler technique because of the high photon efficiency and general maturity of the 10 micron technology. The high-power, high-stability, long-lifetime laser is undoubtedly the most important single component of such a lidar system. The development of such a laser is proposed, covering such aspects as resonator design, discharge excitation, use of catalysts for lifetime improvements, etc. The accuracy requirements for pointing and lag-angle correction for the pulse time of flight are stringent and must be considerably less than the beam divergence. A careful theoretical and experimental study of the problems of pointing accuracy and lag compensation is therefore needed.

The development schedule for the wind lidar is for an instrument conceived to operate in an 800 km polar orbit for operational meteorology. A mission opportunity on the co-orbiting platform (lower orbit: 300 km) of the Space Station with a nonscanning instrument could relax the technology requirements and bring forward possible instrument deployment.

Interferometric techniques are also recognised as showing considerable promise, and it is suggested that progress in this field be closely monitored, if appropriate, in the context of a feasibility study. For the laser altimeter, an adaptation study to investigate to what extent the envisaged backscatter lidar can be adapted to meet altimetry objectives for solid-Earth or ocean/ice disciplines is proposed.

High priority is recommended for research and development work on critical-component lifetime and reliability, and that of the flash-lamp. Furthermore it is recommended to carry out:

- a science study, to assess quantitatively the requirements and benefit of complementary measurements. Such a study will serve as an input for resolving for sampling and horizontal-resolution problems;
- a global system study, to define the needs and requirements of the backscattering lidar instrument (suitable detectors and detection system, receiver optics, scanning telescope configuration and constraints, signal processor, data acquisition and transmission).

## 6.1 Backscatter Lidar

**6.2 DIAL Lidar** Research and development work on suitable vibronic laser crystals (e.g. Ti-Sapphire or a similar high-quality crystal) is recommended since their intrinsic tunability and good efficiency are particularly important for DIAL.

The measurement performance achievable will depend critically on the laser performance, which is expected to vary for different types of measurements (water vapour, temperature or pressure). Effort should therefore be devoted to adequate wavelength-control techniques, suitable spaceborne wavemeters, and Doppler shift corrections. A scientific study should also be carried out prior to a subsequent instrument system study to identify and define science and instrument characteristics and requirements in the context of available flight opportunities.

**6.3 Wind Doppler Lidar** For wind measurements, both coherent (CO<sub>2</sub> laser technology) and incoherent (primarily Nd-YAG laser technology) Doppler lidars need to be considered.

For the more advanced coherent CO<sub>2</sub> Doppler wind lidar, it is recommended that research and development effort should focus on the critical aspects of laser performance (line width, frequency stability, chirping, energy, pulse length), lifetime, pointing accuracy and precision of lag angle compensation.

For the Nd-YAG route, a study to assess the various critical areas (laser energy requirements, pointing, eye safety, etc.), evaluate the allowable degree of trade-off between them, and identify the implications for achievable measurement accuracy, is recommended.

This study should be followed by a technology-development effort if such a system is considered feasible for spaceborne operation.

**6.4 Laser Altimeter** Here the Working Group recommends an accommodation study, for the adaptation of a backscattering lidar instrument to altimetry applications, and to identify instrument characteristics in the context of the selected application areas and their objectives.



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